NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

JOINT APPLIED PROJECT

AN ANALYSIS OF THE GPS R&D PROGRAM AS A CASE STUDY ILLUSTRATING DOD R&D AND ITS ASSOCIATED SUCCESSES TO JUSTIFY THE CONTINUED INVESTMENTS INTO AND SUSTAINMENT OF DOD R&D BUDGETS

September 2016

By: **Kenny Juncu**
Michael Livaudais

Advisors: **Brad Naegle**
Joshua Gomer

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2016	**3. REPORT TYPE AND DATES COVERED** Joint applied project	
4. TITLE AND SUBTITLE AN ANALYSIS OF THE GPS R&D PROGRAM AS A CASE STUDY ILLUSTRATING DOD R&D AND ITS ASSOCIATED SUCCESSES TO JUSTIFY THE CONTINUED INVESTMENTS INTO AND SUSTAINMENT OF DOD R&D BUDGETS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Kenny Juncu and Michael Livaudais			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The purpose of this joint applied project is to examine the trends in funding of the Department of Defense (DOD), assess the importance of robust research and development investment on national security and warfighters' capabilities, and justify continued devotion to funding DOD research and development (R&D).

This research looks at the history of DOD R&D budgets and examines R&D spending trends and the importance of R&D to warfighters and humanity. An evaluation of the DOD's R&D infrastructure and the impacts that drive future funding decisions are also part of this research.

The case study of GPS is the primary example to defend the importance of R&D. The case study ranges from the history of its discovery, how it applies to the military, the associated compounded benefits to other discoveries and technological improvements due to the maturation of GPS, to the associated benefits to the U.S. economy.

Maintaining the proper level of DOD R&D funding in each fiscal year is imperative to allowing DOD agencies to pursue R&D projects that enhance the warfighter's future competencies and well-being in combat and in disaster-relief circumstances. Appropriate R&D funding also provides for accelerating mature technology solutions to be deployed with the current fighting force.

14. SUBJECT TERMS DOD, R&D, GPS, budgets, military, funding			**15. NUMBER OF PAGES** 81
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

AN ANALYSIS OF THE GPS R&D PROGRAM AS A CASE STUDY ILLUSTRATING DOD R&D AND ITS ASSOCIATED SUCCESSES TO JUSTIFY THE CONTINUED INVESTMENTS INTO AND SUSTAINMENT OF DOD R&D BUDGETS

Kenny Juncu, Civilian, Department of the Navy
Michael Livaudais, Civilian, Department of the Army

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN PROGRAM MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2016

Approved by: Brad Naegle

Joshua Gomer, Ph.D.

Brad Naegle
Academic Associate
Graduate School of Business and Public Policy

THIS PAGE INTENTIONALLY LEFT BLANK

AN ANALYSIS OF THE GPS R&D PROGRAM AS A CASE STUDY ILLUSTRATING DOD R&D AND ITS ASSOCIATED SUCCESSES TO JUSTIFY THE CONTINUED INVESTMENTS INTO AND SUSTAINMENT OF DOD R&D BUDGETS

ABSTRACT

The purpose of this joint applied project is to examine the trends in funding of the Department of Defense (DOD), assess the importance of robust research and development investment on national security and warfighters' capabilities, and justify continued devotion to funding DOD research and development (R&D).

This research looks at the history of DOD R&D budgets and examines R&D spending trends and the importance of R&D to warfighters and humanity. An evaluation of the DOD's R&D infrastructure and the impacts that drive future funding decisions are also part of this research.

The case study of GPS is the primary example to defend the importance of R&D. The case study ranges from the history of its discovery, how it applies to the military, the associated compounded benefits to other discoveries and technological improvements due to the maturation of GPS, to the associated benefits to the U.S. economy.

Maintaining the proper level of DOD R&D funding in each fiscal year is imperative to allowing DOD agencies to pursue R&D projects that enhance the warfighter's future competencies and well-being in combat and in disaster-relief circumstances. Appropriate R&D funding also provides for accelerating mature technology solutions to be deployed with the current fighting force.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

ABL	Allegany Ballistics Laboratory
ABM	Anti-ballistic Missile
ACD&P	Advanced Component Development and Prototypes
AFOSR	Air Force Office of Scientific Research
APL	Applied Physics Laboratory
ARRA	American Recovery and Reinvestment Act
ATD	Advanced Technology Development
CIA	Central Intelligence Agency
CND	Council of National Defense
DAA	Defense Authorization Act
DARPA	Defense Advanced Research Projects Agency
DAS	Defense Acquisition System
DLE	Defense Laboratory Enterprise
DOD	Department of Defense
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
FBI	Federal Bureau of Investigation
FFRDC	Federally Funded Research and Development Center
GDP	Gross Domestic Product
GOGO	Government Owned Government Operated
GPS	Global Positioning System
GWOT	Global War On Terrorism
IED	Improvised Explosive Device
JIEDDO	Joint Improvised Explosive Device Organization
LORAN	Long Range Navigation
LOS	Line of Site
MILCON	Military Construction
MILPERS	Military Personnel
NAVSEG	Navigation Satellite Executive Group
NDRC	National Defense Research Committee

NNSA	National Nuclear Security Administration
NSA	National Security Agency
NSF	National Science Foundation
NSF	National Science Foundation
O&M	Operation and Maintenance
OCO	Overseas Contingency Operations
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OSRD	Office of Scientific Research and Development
PMA	Portable Maintenance Aid
PRN	Pseudorandom Noise
QDR	Quadrennial Defense Review
R&D	research & development
RADAR	Radio Detection and Ranging
RDF	Range and Direction Finding
RDT&E	Research Development Test and Evaluation
ROI	Return on Investment
S&T	Science and Technology
SDD	System Development and Demonstration
SECOR	Sequential Correlation of Range
SPS	Standard Positioning System
UAV	Unmanned Aircraft Vehicle
WMD	Weapon of Mass Destruction

I. INTRODUCTION

As a critical element of innovation, research and development (R&D) has been one of the key elements of progress, allowing companies to create new products and enhance existing ones. R&D is also an important mechanism used by companies to increase their market share and create new competitive advantages. R&D plays a critical role in enhancing/supporting the United States' national security as well as long-term scientific and technological future applications/capabilities for our warfighters. Examples include: robotics, cybersecurity, advanced sensors, the internet-of-Things, advance material science and predictive analytics.

The National Science Foundation (NSF) (2010) defines "research" as: "A systematic study directed toward fuller scientific knowledge or understanding of the subject studied." NSF also defines "development" as: "A systematic application of knowledge or understanding directed toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements."

The DOD fosters a climate conducive to establishing and developing R&D cooperation between DOD agencies and private sectors. Such cooperation is critical in connecting people, resources and strategies. Together, they have developed, improved, and promoted new technologies, future weapons systems, and sustained technological superiority that our military has benefited from for several decades.

The DOD is also endorsing multilateral international research and development agreements and information exchanges with partner nations and allies to expand the R&D information base and to assess diverse solutions for similar technical challenges.

As the Secretary of Defense, Chuck Hagel stated in *2014 Quadrennial Defense Review* (QDR):

> Investment decisions will ensure that we maintain our technological edge over potential adversaries, and that we advance U.S. interests across all domains. Staying ahead of security challenges requires that we continue to innovate, not only in the technologies we develop, but in the way U.S.

> forces operate. Innovation—within the Department and working with other U.S. departments and agencies and with international partners—will be center stage as we adapt to meet future challenges. (Hagel, 2014)

A. OVERVIEW OF DOD BUDGETS

The responsibility of Congress with regard to federal budget practice was changed in 1974 with the release (enactment) of the Congressional Budget Control Act, which is the blueprint for all four budgetary phases. They are: formulation, enactment, execution, audit and evaluation. Congress also established the Congressional Budget Office and was granted the authority to direct federal spending. Standing budget committees were created in the Senate and House of Representatives (Amadeo, 2016b).

The Senate and House of Representatives could use their budgets to negotiate during the time the appropriation bills are finalized. Budget development starts in the early fall, one year prior to the new fiscal year, which begins October 1 of the preceding calendar year. For example, for fiscal year 2017 (which begins Oct. 1, 2016), the budget process started in the fall of 2015 (i.e., one year prior). During this time, the Executive Office of Management and Budget (OMB) compiles budget requests received from federal agencies, and submits the final compiled budget for the subsequent fiscal year to the president in December. The legal deadline for release of the president's budget recommendations to Congress is February of each year. These recommendations outline the president's funding priorities. Part of the budget process constitutes a yearly concession between the president and Congress in defining a discretionary spending plan. The Congressional Budget Office provides a detailed review of the president's yearly budget and supports Congress by providing unbiased review of the budget. After the Budget Resolution is approved in mid-spring, Congress develops spending appropriation bills that fund every agency in the discretionary budget. Before October 1 (and thus, the new fiscal year), these appropriation bills should be signed into law by the president (Christensen, 2012, pp. 3–7).

Acquisition programs are financed through budgets authorities provided by Congress. Budgets, as a policy, disclose the government's main concerns; they are complex and difficult to assess. An Appropriation act is a mechanism used by Congress to provide the budget authority used to finance program efforts. Each appropriation act has a certain purpose and defines/limits the amount of budget authority allocated by Congress annually (per the Defense Appropriations Act) that is used to make payments to various agencies. The major appropriation categories received by DOD are listed below:

- Research, Development, Test and Evaluation (RDT&E)
- procurement
- Operation and Maintenance (O&M)
- Military Personnel (MILPERS)
- Military Construction (MILCON)

Given that the appropriation categories listed above are generic groupings, appropriation expenditure accounts are used by Congress to clearly specify particularities of each appropriation account. The appropriation expenditure accounts are assigned four-digit codes, of which each DOD Department has a two-digit code for convenience/designation purposes. Each appropriation act is signed into law by the president (Christensen, 2012, pp. 3–7).

1. DOD R&D Budget

Each fiscal year (e.g., FY16), a budget request should be released by the president in February of the previous year (2015). The budget includes both mandatory and discretionary spending. Mandatory spending includes Medicare, Social Security, Medicaid, etc. Discretionary spending separately contains a general defense and nondefense budget and a defense and nondefense R&D budget. For 2016, 29% of the total budget would be allocated to discretionary spending accounts (Hourihan & Parkes, 2016). This discretionary spending is addressed through the annual appropriations process.

In the DOD, there are two types of budgets: investment-type budgets and expense-type budgets. R&D is one of the common appropriations in our defense budget and is part of expense-type category. The obligation period for R&D is two years. Typically it covers:

- trade studies
- basic and applied research
- system design and integration
- operational system improvements
- systems engineering and program management
- advanced technology development
- system test and evaluation
- development, fabrication, assembly and test of prototypes
- system development and demonstration

All the activities listed above are estimated and represented by the following Defense Acquisition System (DAS) phases:

- Material Solution Analysis Phase
- Technology Development Phase
- Engineering & Manufacturing Development Phase

2. DOD R&D Budget Categories

Within the defense department, R&D activities are segmented as being one of two portfolios: DOD R&D portfolio and defense-related R&D portfolio. The DOD R&D portfolio is funded through the DOD R&D budget, whereas the defense-related R&D portfolio is funded through the National Nuclear Security Administration (NNSA), which is part of the Department of Energy (DoE).

The DOD Financial Management Regulation identifies and defines the following R&D activities:

- Science and Technology (S&T) Activities
    - basic research (6.1)
    - applied research (6.2)
    - Advanced Technology Development (ATD) (6.3)

- Weapons Development Activities
    - Advanced Component Development and Prototypes (ACD&P) (6.4)
    - System Development and Demonstration (SDD) (6.5)
    - RDT&E Management Support (6.6)
    - Operational System Development (6.7)
- R&D Equipment
- R&D Facilities (RAND Corporation 1998)

S&T Initiatives: countermeasures to asymmetrical threats, ballistic missile defense, moving-target tracking, network centric warfare, unmanned land, air, space, sea, and underwater systems, etc. (Etter, 2001).

3. DOD R&D Funding History

During World War I, the Council of National Defense (CND) was instituted to fund and oversee all defense research activities supporting the military. In 1940, the National Defense Research Committee (NDRC) was founded to manage, direct, and carry out scientific research, development and production on warfare systems. This organization did not have the funding required to bring the outcome of the research into the next phase of production. In response, President Roosevelt, through an executive order, created the Office of Scientific Research and Development (OSRD) that provided the funding and contracting infrastructure for the research, development, and experimental investigations activities performed by NDRC. The OSRD had spent $450 million by the end of the World War II on developing new and more reliable weapon systems. In the postwar era, OSRD played an important role in engaging industry and universities in defense R&D activities. During the Cold War period, defense R&D spending soared, peaking in 1960 when it accounted for 80% of federal R&D funds, with emphasis on cutting edge weapon systems development. This approach elevated the U.S. as a leader in defense technological development above Europe and everywhere else in the world. Between 1960 and 1980, the defense R&D funding constituted approximately 50% of the federal R&D budget. (Steinbock, 2014). During the Reagan presidency, the military's investment in advanced-technology development and acquisition investment increased such that defense R&D was above 0.80% of GDP. Inversely proportionate with those of the U.S., defense budgets around the world fell after the collapse of Soviet Union. For the U.S., defense R&D spending surged again after the events of September 2001, reaching over $50B in 2003 and exceeding $83B in 2009. By 2015, the defense R&D budget approached $68B (Weiss & Vahey, 2014).

4. Summary

R&D obligations are only a fraction of the overall DOD expenditure in developing cutting edge technology for the warfighters. Yet, the trend for funding R&D is in an overall decline. More recently, in FY2014, the DOD obligated around $28B on R&D, less than was invested 15 years ago, in FY1998 (roughly $31B after adjusting for inflation).

The graph in Figure 1 shows that for the past 20 years, the defense R&D obligations dropped from 19%, in FY 1998 to 10% in FY 2014.

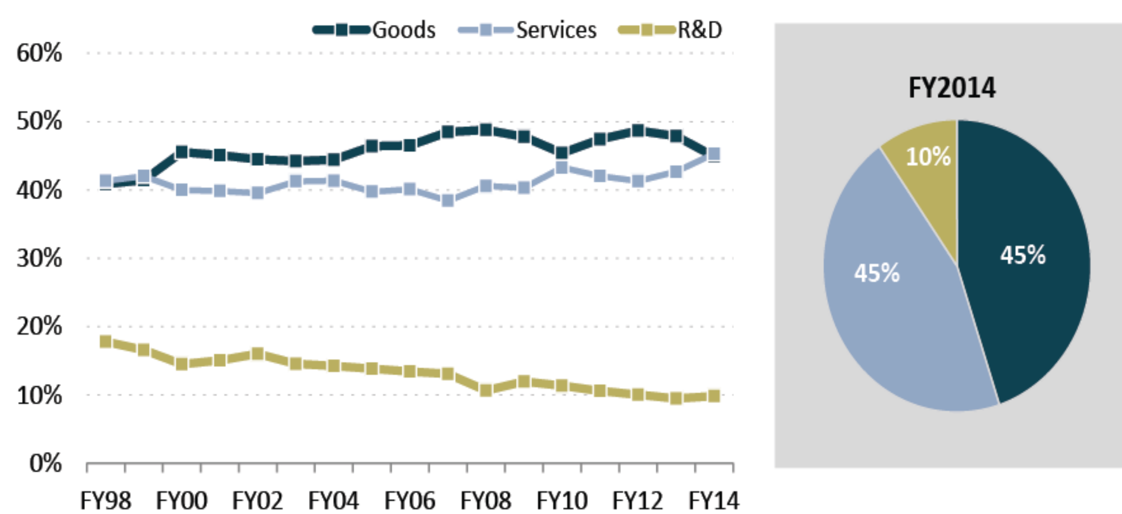

Figure 1. DOD Obligations by Major Categories. Source: Schwartz, Ginsberg, & Sargent (2015).

B. THESIS STATEMENT / SCOPE OF RESEARCH AREAS

1. Thesis Statement

An analysis of The Global Positioning System (GPS) R&D Program as a case study illustrating DOD R&D and its associated successes to justify the continued investments into and sustainment of DOD R&D budgets.

2. Secondary Questions

The secondary questions associated with defending the thesis statement are as follows:

- What R&D organizations were in place to successfully develop the GPS system we know today?
- What budgets and schedules influenced the GPS development?
- What are the implications of GPS successes resultant from R&D investments?

Research and development is critical in establishing where military Services can improve warfighters' capabilities. The level of current defense R&D funding is especially important to the challenge of responding to global security risks and maintaining military strength. Given the DOD budget pressure (downward) and the defense R&D funding trend for the past several years, DOD faces challenges sustaining adequate R&D capabilities for the U.S. to preserve a leading military advantage and help develop sustainable, cutting-edge technology needed by the warfighter.

Is the current level of defense R&D budget adequate to maintain and upgrade the existing military systems and support the development of future defense needs? In 2014, Mr. Frank Kendall – the Under Secretary of Defense for Acquisition, Technology and Logistics – expressed his concerns to emphasize the importance of maintaining a robust DOD R&D investment for warfighters' capabilities; he stated the following in his article "Protecting the Future:"

> Most of all, however, I am concerned about protecting the adequacy of our research and development (R&D) investments in capabilities and systems that will allow us to dominate on future battlefields and keep engineering

> design teams who develop advanced defense systems. (Kendall, 2014, p. 2)

In the same article, Mr. Kendall emphasized the issue and urgencies surrounding defense R&D being inadequately funded, and stressed the following points:

- "U.S. technological superiority is not guaranteed – and is under constant attack by state actors such as Russia and China.
- As such, research and development is actually a fixed cost, NOT a variable cost. The implication is that reducing R&D proportionally to procurement is a risk with huge negative implications for the nation.
- Time is a precious, unrecoverable asset. We cannot get back lost R&D time" (Kendall, 2014, p. 3).

With DOD budgets facing continuous scrutiny and receiving high levels of visibility, the quest to curtail spending within the government and DOD is effervescent. When programs short on funding have been deemed a high priority, the funding is cut from other programs deemed less important. Often times, R&D is the recipient of the cuts.

This research effort will focus on the following areas:

- historical overview of DOD R&D
- DOD R&D infrastructure
- articulation of the importance of DOD R&D through many experienced successes, specifically the Global Positioning System (GPS).
- DOD R&D budget analysis
- GPS case study analysis

These research areas will support the thesis on the defense of why past investments in DOD R&D have been worthwhile, and why investments in the future should continue.

II. HISTORY OF DOD R&D

“Science is the shield of the free world.”

—Louis Ridenour

Creating and sustaining a healthy R&D competence will necessitate an alignment of many things, including an improved R&D strategy, a well-defined mission for national security, laboratories and equipment, predictable funding, and an experienced scientific and engineering workforce to carry out the strategy. Some of the disruptive, revolutionary research and development programs sponsored by DOD had a powerful impact on nation’s defense capabilities, fundamentally changed military strategies and also shaped the defense R&D (Ehrhard, 2008).

A. R&D’S ROLE IN NATIONAL SECURITY

The concept of Research and Development (R&D), as most applicable to the current day definition within DOD, started just before World War II. Following FY38, and the years leading up to the U.S.’ foray into WWII, there was a significant shift in focus and resources toward the employment of scientists and physicists. Before this change in mindset, the traditional focus was on engineers. The U.S. sought to implement a vision to strengthen both offensive and defensive postures (national security) that consisted of unifying the capabilities and output of both engineers and scientists. The Office of Scientific Research and Development (OSRD), formally established in 1941, was the main beneficiary/recipient of these resources. The director of OSRD reported directly to President Roosevelt, who allowed essentially unlimited resources to execute their mission. The Manhattan Project, still considered the most extensive research program in U.S. history, fell under OSRD management. The notion of National Security was bolstered due to the proactive vision and execution of R&D regarding the creation of the atomic bomb, deemed a Weapon of Mass Destruction (WMD) (Spiers, 2000).

R&D played a significant role in solidifying National Security. The vision for enhanced R&D, and the notion of empowering scientists to conduct militaristic research originated from outside the U.S. In late 1939, President Roosevelt was approached by a group of scientists to commence a research program to focus on a groundbreaking discovery that would assist in the creation of the atomic bomb ("Encyclopedia of the New American Nation" n.d.). Scientists from foreign countries were active participants and employed under the Manhattan Project. Many of these scientists were Jewish defectors fleeing the holocaust and active WWII conflict in Europe. As the conflict escalated, the U.S. began to shroud its research and development efforts in secrecy to ensure the rest of the world did not realize its interests, vision, and final products that were to result from extensive research. These results led to improved National Security and set the stage for the creation of other security agencies. These agencies were chartered with the protection of sensitive datasets and the assurance that foreign countries did not know or have access to U.S. military intellectual property (Lee, n.d.).

As the U.S. began to safeguard its R&D, its reputation for facilitating research began to spread. This encouraged foreign scientists with ideas, yet without resources, to pursue relationships with the U.S.: "In 1940, the eminent British scientific leader Sir Henry Tizard flew to Washington on a secret mission to persuade the U.S. government to cooperate in building a system of radar and radar countermeasures" ("Encyclopedia of the New American Nation," n.d.). Under OSRD, British scientists were able to leverage the vast resources of the U.S. and produce penicillin in mass quantities.

As U.S. investments in R&D grew in the early 1940s, along with tangible output and success, its paranoia about foreign access to U.S. intellectual property and "secrets" continued to grow. Not only did the U.S. act on the importance of safeguarding both their intelligence and intellectual property, but it also decided to stand up organizations that focus on the active pursuit of knowledge of foreign programs regarding Science and Technology (S&T) and military intelligence. To further articulate the lengths the U.S. took to safeguard R&D efforts, Harry Truman, vice president to President Roosevelt, did not even know the Manhattan Project existed until Truman assumed the presidency after Roosevelt's death in 1945. These notions laid the groundwork to form specific organizations, such as the Central Intelligence Agency and the National Security Agency. The long term impacts to the investment and sustainment of DOD R&D has led to many discoveries, creations, and implementations that exceed the boundaries of military applications and National Security. Such boundaries even exceeded the betterment of the U.S., as many countries have benefitted from U.S. R&D (Kester, Research America).

B. R&D INFRASTRUCTURE

Throughout World War I, important military innovations were developed such as gas warfare, aviation, military electronics, artillery field spotting, interception and jamming of radio transmissions, etc. Still, due to organizational limitations, the scientific inputs to the military during that period were minimal. Prior to World War II, U.S. Defense spending was low due to a favorable security situation (and thus, less needed). In peacetime until World War II, the United States government supported development of technology and innovation using policies associated with specific national purposes. R&D was primarily used by large corporations during that period.

R&D efforts during World War II influenced technological innovations strategies; and as a result, great scientific discoveries were made such as: the development of the radar system, the Manhattan Project, the aircraft carrier, the jet engine, nerve gases and the development of systematic methods of weapons performance analysis and requirements. R&D efforts also paved the road and influenced defense R&D management methods used for projects developed during the postwar. These projects, along with other wartime technological developments, generated the guidance and framework that are used today by defense programs and showed how warfighters, researchers, and industry worked together and were able to reach world-class technological advancement (Finnamore, 2015).

One other aspect that contributed to successful development of these weapon systems was the partnership between the government and the scientific research community. Experience gained from the war, along with government support, led to continuation of R&D in postwar time. Postwar innovations were strongly affected by defense procurement and R&D due to a great demand for weapons systems. Defense funding and supporting legislation had a critical role in maintaining the research activities performed by academia and defense contractors supporting such demand. Technology development's criticality to national security was understood after the development of the atomic bomb during World War II. It was also understood that the superiority of a country relies on its technological capabilities. Such understanding triggered the defense spending, which was $500M in 1945, to increase to $6.5B in 1966 (Leitenberg, n.d.).

1. Establishment Of DOD R&D Centers

a. Federally Funded Research and Development Centers (FFRDCs) Overview

For more than seventy-five years, Federally Funded Research and Development Centers (FFRDCs) supported defense-related objectives. Established in the 1940s under Federal Acquisition Regulation 35.017, FFRDCs brought engineering and scientific expertise that was required to address demanding defense challenges. Leading edge research necessitates modern facilities, state-of-the-art equipment and sustained technical talent. R&D institutions under FFRDC were privately owned and operated and provided the scientific expertise in support of the military community, a competence/skill that was not available within the government. There are three types of FFRDC centers performing different extramural activities: study and analysis centers, laboratories, and systems engineering.

One such organization, instituted in 1942, was the Applied Physics Laboratory (APL) at Johns Hopkins University. APL's mission was to guide contractors and universities in designing and developing weapon systems. Other labs were also established during the same period: Harvard Underwater Sound Laboratory, Jet Propulsion Laboratory–California Institute of Technology, and the Radiation Laboratory – Massachusetts Institute of Technology (Hruby et al., 2011).

The FFRDC laboratories came under Congressional scrutiny in the mid-1970s. Besides the fact that many believed these laboratories were overfunded, there were also complaints from the Agencies that the research performed was too scientific, did not align with the DOD requirements, and could not be used by the military.

In late 1969, Senator Michael Joseph introduced Section 203, known as the Mansfield Amendment, to the Military Authorization Act. This Amendment restricted the

DOD from spending appropriated funds for any study or R&D tasks that did not support warfighter CONOPS (Harwit, 2013). Due to lack of defense R&D funding—as a result of this Amendment—almost 45% of research performed for the military was dropped by 1977. Since the FFRDC laboratories could not be adequately funded, most of these centers could not survive; others realigned their business processes toward not-for-profit or private sectors. The second round of examinations with regard to FFRDC activities came in 1990 when the DOD was instructed that FFRDCs must be used for government R&D only in situations when the government did not have the infrastructure and required skills to execute the projects and perform the studies related to defense needs. As of 2011, there were only twenty-six R&D facilities (Lincoln Laboratory, Software Engineering Institute, etc.), nine System Analysis facilities (e.g., Institute for Defense Analyses, RAND Corporation) and five System Engineering centers (e.g., MITRE C^3I, Aerospace Corp.) under FFRDC with annual funding received from different DOD sponsoring agencies (Navy, Air Force, Army, OSD, etc.) of up to $2.2B (Hruby & Manley, 2011, p. 27).

The support provided to DOD agencies by these centers was invaluable, especially in responding to advanced technological defense system needs and new national security developments. Without the proper funding to support the FFRDC centers, and with a lack of highly needed R&D technological expertise of DOD agencies to respond to the nation’s development needs, the U.S. would have difficulty maintaining its defense technological leadership. For the last several years, there have been ongoing dialogues dedicated to defining the boundaries between the FFRDC centers involvement in defense R&D support and government workforce roles in these activities—still without a clear outcome. FFRDC institutions are uniquely positioned to address challenging unforeseen defense problems such as Improvised Explosive Devices (IEDs). These institutions were able to bring together specific technical skills and created the Joint Improvised Explosive Device Organization (JIEDDO), and through collaborative work, developed a solution mitigating the threat. This was a vital solution to our warfighters (Alterman, 2012). More than 90% of DOD FFRDC funding comes out of DOD programs appropriations, programs that FFRDC supports (U.S. Congress, 1995).

Congress established financial ceilings on DOD-appropriated money that could be allocated to DOD FFRDC centers. The work emphasis of these centers shifted over the years, but the core mission still remains today: responsiveness, objectivity, and most important, being a reservoir of knowledge and support for ongoing military missions and future requirements. The list below provides today's FFRDC centers and their sponsoring agencies:

- Department of the Air Force – Aerospace Federally Funded Research and Development Center; Project Air Force
- Department of the Army – Arroyo Center
- Department of the Navy – Center for Naval Analyses
- National Security Agency – Center for Communications and Computing
- Office of the Under Secretary of Defense for Acquisitions, Technology and Logistics – Lincoln Laboratory; National Defense Research Institute; National Security Engineering Center; Software Engineering Institute. (Master Government List of Federally Funded R&D Centers, 2016)

b. DOD Laboratories

The Defense Laboratory Enterprise (DLE) organization was created during World War II to enhance combat capabilities. This organization encompassed all the defense laboratories that were operated by the Navy, Air Force, and Army.

In 1946, the United States Office of Naval Research (ONR) was established. ONR was the main sponsor of fundamental research performed by U.S. researchers. ONR was established "in recognition of the need to plan, encourage, and support basic research in our universities, our in-house laboratories, and the private industrial groups in those areas of knowledge that seem to be most relevant to long-range Navy requirements" (Leitenberg, 2000, p. 16).

The research performed by ONR was mission-oriented and supported naval operations. Some of the basic research conducted at that time was related to remote sensing of the sea surface, acoustics, deep moored and drifting buoys, etc.

The Air Force established their research organization, Air Force Office of Scientific Research (AFOSR), in 1951 with the objective of engaging in "contracts with educational institutions for research in broad general fields on problems which, without being directed toward definite applications, are of definite interest to the Air Force" (Leitenberg, 2000, p. 17).

By 1976, the Department of Defense had 114 laboratories: Army had 50, Navy had 35 and Air Force had 29. R&D activities performed in these labs were coordinated through the Office of the Secretary of Defense (OSD) (Leitenberg, 2000, p. 23).

By 1990, the budget for the government-owned, government operated (GOGO) R&D activities was $ 8.5B with almost 45% spent in house on specific technical research programs. 65% of the budget was contracted out to FFRDC labs, defense contractors, and universities. From 1985 (with a budget of $390B) through 1995 (budget of $295B), the defense budget dropped 35% (United States General Accounting Office Washington, D.C., 20548, 1995). This significant decline in defense budget during this period was a result of the end of Cold War. In 1989, DOD revealed the new weapons systems acquisition process. This new acquisition process shielded the defense R&D from substantial budget cuts, and thus, R&D spending declined only 12% during three years. With the focus toward consolidation in DOD R&D infrastructure (laboratories and personnel) in 1991, through the Defense Authorization Act, Congress instructed all agencies to reassess their operations, cut back the R&D workforce by 20%, revisit DOD R&D laboratory missions and functions, and close or combine some of the laboratories until 1995. The intent of the consolidation and downsizing of laboratories and reduction in the civilian workforce was to (1) reduce cost, and (2) achieve higher quality and improve effectiveness. As a result of the direction provided by Congress, the Air Force restructured all its laboratories into four and assigned them divisions per product; Army and Navy also proceeded with realignment of R&D facilities and closed some of the labs while consolidating others.

Defense R&D laboratories are a pillar for technological development and supporting infrastructure that helps researchers accomplish their work. The Defense Laboratory Enterprise organization allows DOD to maintain a strong core technical base and provides the military community with the technical competency and support to achieve their mission and be the most technologically advanced military.

Presently, the defense R&D laboratories are located across twenty-two states and employ over 38,000 researchers, engineers, and computer scientists and over 67,000 employees. As of 2016, the numbers of labs per agency are listed below:

- Navy: 26 labs
- Air Force: 15 labs
- Army: 36 labs

Re-evaluation of each laboratory's mission resulted from specific technical needs required by the military. Research programs and activities overseen by DLE are mission-driven and account for over $30B of work per year. Research done in-house by DOD researchers as compared to that performed by universities, FFRDC labs, and defense contractors has a 50/50 distribution. In addition to research performed for the military, the labs are required under the technology transfer initiative, to converge non-sensitive intellectual property applications that are developed specifically for the military into solutions that could be transferred into the public sector.

Two of the top research agencies within DOD are Defense Advanced Research Projects Agency (DARPA) and Defense Threat Reduction Agency (DTRA). Both agencies are under the Office of the Secretary of Defense (OSD). DARPA and DTRA fund and oversee programs performed by non-DOD researchers and external laboratories. Currently, DARPA has 219 government employees and the organization's budget for FY15 was $2.9B.

Table 1 shows the Federal obligations for research, by agency and performer for FY 2010 (dollars in millions). Preliminary Federal obligations for research, by agency and performer for FY 2015 are provided in Table 2 (dollars in millions).

Table 1. FFRDC R&D Obligations per Agency, FY2010.

			Extramural								
			United States and U.S. territories								
Agency	Total	Intramural	Industry	Industry FFRDC	Universities and colleges	University FFRDC	Other nonprofits	Nonprofit FFRDC	State, local governments	Foreign
Department of Defense	7,065.4	2,121.1	2,714.3	81.9	1,830.8	59.9	176.8	27.9	1.8	50.5
Defense agencies and activities	2,443.5	280.6	1,302.3	66.7	638.7	51.7	63.9	16.8	0.0	22.4
Chemical and Biological Defense	310.0	116.9	89.5	10.9	66.0	2.4	13.7	2.9	0.0	7.4
Defense Advanced Research Projects Agency	1,627.2	92.7	1,047.6	5.3	394.6	19.9	43.9	9.4	0.0	13.5
Defense Threat Reduction Agency	268.3	37.2	114.4	49.5	53.0	4.2	6.0	2.1	0.0	1.4
Office of the Secretary of Defense	212.2	30.2	28.5	0.8	124.9	25.0	0.2	2.3	0.0	0.0
Special Operations Command	25.6	3.5	22.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Department of the Air Force	1,678.2	735.4	518.0	2.2	374.0	5.1	24.3	4.7	0.7	13.4
Department of the Army	1,675.1	671.6	577.8	5.3	364.2	0.7	52.4	1.8	0.0	1.0
Department of the Navy	1,268.4	433.4	316.1	7.5	453.8	2.2	36.0	4.5	1.0	13.6

Source: National Science Foundation, http://www.nsf.gov/statistics/nsf13326/content.cfm?pub_id=4243&id=2.

Table 2. FFRDC R&D Preliminary Obligations per Agency, FY2010.

	Total	Intramural	Extramural								
			United States and U.S. territories								Foreign
			Industry	Industry-FFRDCs	Universities and colleges	University-FFRDCs	Other nonprofits	Nonprofit-FFRDCs	State, local governments		
Dept. of Defense	6,901.7	2,045.3	2,537.0	59.5	1,822.5	78.6	237.2	48.3	1.8		71.2
Defense Advanced Research Projects Agency	1,554.0	66.5	987.7	11.5	373.1	12.1	81.8	9.4	0.0		11.7
Dept. of the Air Force	1,630.6	666.0	522.3	1.4	332.2	1.4	84.6	5.4	0.3		16.1
Dept. of the Army	1,456.9	479.3	509.5	0.2	448.5	4.2	6.7	4.0	0.0		4.2
Dept. of the Navy	1,448.4	522.6	328.3	7.4	491.1	16.2	52.8	6.3	1.4		21.9
Other defense agencies	811.6	310.3	189.1	38.7	177.5	44.5	11.1	22.9	0.0		17.2

Source: National Science Foundation, National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development, FYs 2014–16.

As mentioned above, in 2011 there were 40 FFRDC centers supporting DOD agencies with a diverse array of research activities. Currently there are only nine DOD FFRDC centers.

In 2010, Congress appropriated $7.6B (2015 inflation-adjusted) to DOD agencies for funding intramural and extramural research activities. In 2015 Congress appropriated $6.9B for the same research activities, 2.31% less (actual: 10.13% less, inflation-adjusted) than in 2010 (National Science Foundation, FYs 2010–2012). Examining intramural research funding between 2010 and 2015, there was a 3.5% decrease in funding (11.2% less, inflation-adjusted) in 2015 than 2010. Obligations for extramural research, pertaining to industry and universities, FFRDC saw a 2.5% decrease in 2015 than 2010 (National Science Foundation, FY2014–2016). The defense R&D funding uncertainty throughout the years had a great impact on all FFRDC centers as well as DOD R&D facilities. Such budget cuts resulted in most of the FFRDC centers seriously decreasing their staff and shutting down their operations, while others became private companies. The existence of these research communities, for over 75 years, is owed to the particular organizational structure, the relationship with their sponsors, and their specialized expertise in niche areas that the federal government or private industry could not acquire the know-how to fill. Such expertise to solve time-sensitive defense concerns is critical for our national security and military, it is also very difficult and expensive to re-create it on short notice (Hruby et al., 2011).

2. Human Resources

Research and development is part of the core building blocks of defense. The decline in R&D budget in the last few years has raised questions regarding its impact on developing new technologies, updating existing platforms, and modernizing the defense R&D infrastructure. For the past few years, one of the challenging tasks has been maintaining the defense R&D infrastructure and proper force structure that supports R&D programs with a defense R&D budget in decline. A robust defense R&D competency usually encompasses a highly technical, capable workforce that could engage fast and provide solutions to national and international threats, be able to assess the long and short-term country's defense needs, and work in partnership with the private sector R&D. Strong R&D financial health helps to maintain the readiness level and strength of the military, while keeping laboratories, universities, personnel and private sector engaged and ready to respond to national defense needs. In 1990, the defense R&D facilities employed over 100,000 employees (see Table 3); civilian and military with more than half being scientists and engineers (Congress, U.S. Office of Technology Assessment, 1993).

Table 3. Employment in Service RDT&E Facilities.

	Personnel						
Service	**Total**	**R&D**	**T&E**	**Military**	**Civilian**	**Professional**	**Ph.D.**
Army	31,198	21,280	9,918	6,235	24,963	15,593	1,825
Navy	42,186	32,133	10,053	4,730	37,456	20,234	2,138
Air Force	27,245	7,390	19,855	17,228	10,017	9,696	775
Total	100,629	60,803	39,826	28,193	72,436	45,523	4,738

Source: U.S. Department of Defense, Office of the Secretary of Defense, Deputy Director of Defense Research and Engineering/Science and Technology, (1992), *Department of Defense In-House RDT&E Activities: Management Analysis Report for Fiscal Year 1990*, Washington, DC: Author, pp. vi–xiv.

As mentioned previously, due to the decline in defense R&D budget and the 1991 Defense Authorization Act, the DOD agencies were instructed to reduce the R&D civilian work force by 20% until 1995 (Congress, U.S. Office of Technology Assessment, 1993). Restructuring the defense R&D organization, particularly due to lack of funding, is a challenging task and might require revisiting the defense R&D mission. Lack of R&D funding could also have an effect on defense contractors' workforce assigned to support and maintain R&D programs and laboratories. In order to comply with the directives provided in the Defense Authorization Act, defense agencies took the following steps:

- Army's consolidation plan: out of 31,000 employees, eliminate up to 6,000 civilian personnel and realign 3,000 other jobs throughout the agency.
- Navy's restructuring plan was to eliminate 2,280 laboratory positions out of 42,000 employees.

- Air Force eliminated 800 positions out of 27,000 employees working in the labs (Congress, U.S. Office of Technology Assessment, 1993).

Scientists and engineers are the vital components of defense R&D. Maintaining a competent R&D workforce requires involving researchers in important and challenging R&D projects, ultramodern laboratories and facilities, state-of-the-art test and evaluation capabilities, proper training, etc. It also means retaining highly qualified personnel and providing the proper means to improve their technical skills. Preserving the skills acquired by the personnel working in the R&D laboratories and passing down the knowledge to new generations of researchers is also very important in developing future military capabilities. Human resource policies emphasize the need for maintaining a highly qualified workforce knowledgeable in military technology. As the defense budget shrinks, it will also impact the defense contractors supporting R&D projects. This implies that DOD R&D laboratories might have to take over more responsibilities (United States Congress. Office of Technology Assessment, 1992).

To reinforce the above statement, let's examine what Matt Hourihan stated in his study "federal R&D in the FY 2016 Budget: An Overview;" "The overall research increase is devoted to civilian activities, as defense research would be trimmed across multiple accounts." Further, he mentioned that **"**Overall Defense Department basic research activities would decline by 8.3%, with most of the cuts targeted at the military departments" (Hourihan & Parkes, 2016, p. 4).

We can see from Figure 2, almost $65B of the Defense authority is designated for development of the military systems and just $10B for research. The nondefense R&D allocation is mostly for basic and applied research activities.

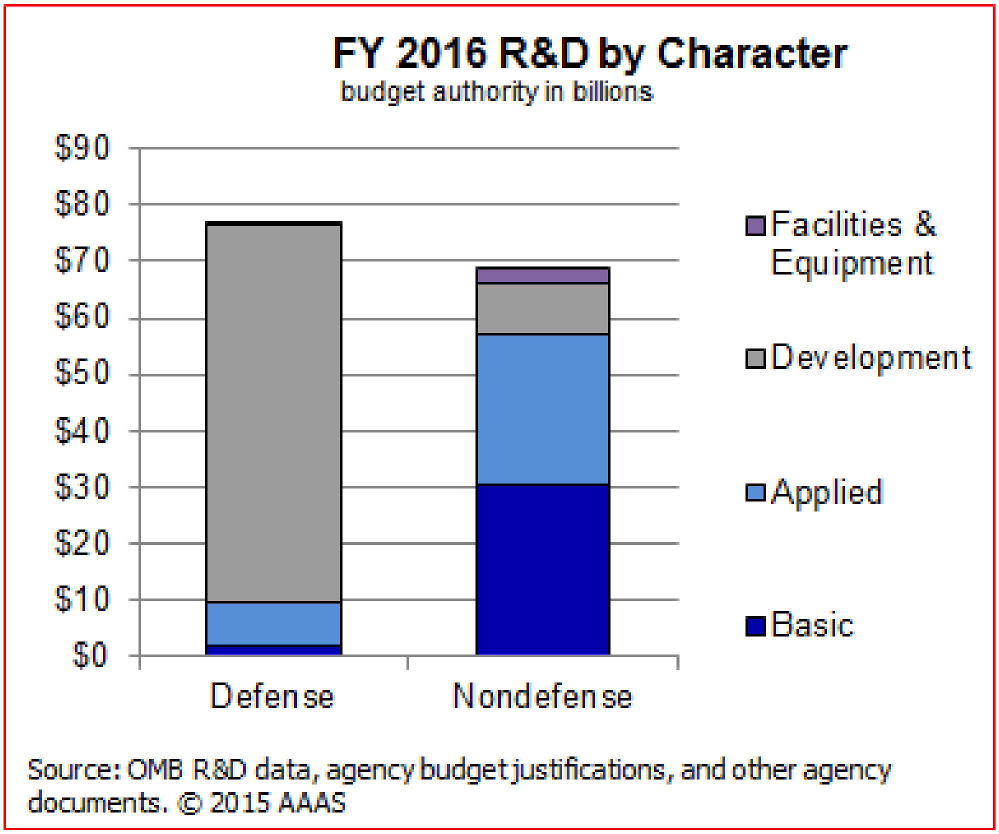

Figure 2. FY2016 R&D Budget Authority. Source: Hourihan & Parkes (2016).

There are two schools of thought with regard to defense R&D spending and the funding level allocated by DOD for research:

- The first school of thought claims that the United States is spending too much on defense R&D, especially on development of high-price, high-maintenance weapon systems that might not be of great value in conflicts such as Iraq and Afghanistan. In his article entitled "Restructuring Defense R&D," Ghoshroy stated that: "In 2011 the United States spent $76B annually on defense research and development, an amount that exceeds the total defense outlays—not just for R&D, but for *all* defense purposes—of every other country in the world except China" (Ghoshroy, 2011). The argument is that the basic and applied research, the critical components of scientific research, are the smallest of defense R&D funding. Ghoshroy further states that "much of what transpires in the name of military research and development is not research in the sense that it produces scientific and technical knowledge widely applicable inside and outside the Defense Department. A large part of defense R&D activity revolves around building very expensive gadgets that are often based on unsound technology and frequently fail to perform as required" (Ghoshroy, 2011).

- The second school of thought reinforces the need and benefit of defense R&D spending and the positive effect of defense scientific innovation on the public sector.

According to Appelbaum (2012), part of the nation's wealth is a result of "the Pentagon's unmatched record in developing technologies with broad public benefits—like the internet, jet engines and satellite navigation—and then encouraging private companies to reap the rewards" (Appelbaum, 2012). It is also claimed that reducing the Pentagon's budget and spending less on defense R&D will have a negative impact on economic growth and that it will increase unemployment. There are differences of opinion regarding defense R&D being the main contributor to the economic growth and that DOD is the main sponsor of funding R&D. It appears that the role of DOD being the main promoter and user of innovation is unanimously accepted; although some scientists maintain that for the past ten years, the commercial industry is spending almost twice as much on research than the federal government.

Despite the differences in opinion of the value or cost of government spending on R&D, history has shown tremendous societal benefits and technological advancements which have resulted from these types of investments (both government and commercial). Also, while political support is not consistent for R&D, it is apparent that economic benefits are also derived from the stimulus of R&D activities by the government (Alterman, 2012).

C. SUCCESSFUL RESEARCH PROJECTS

During World War II, both sides were pushed to break their R&D infrastructure and innovate so as to outwit their opponents with new military technologies. With regard to inventions, WWII produced new technologies that are being used even today. Some of the military research and development performed during the War were the foundation for post-war technologies developed by the industry and used by civilians every day.

Listed below there are several military research discoveries that were invented during WWII and transitioned into the private sector after the war (Finnamore, 2015).

Jet Engine

During World War II, a German engineer designed and developed the first jet engine to be used for a jet fighter to fly in combat. The design of the engine was very inefficient, using a lot of fuel. During the same time in the United Kingdom, another engineer invented his own version of a jet engine, but because of lack of speed, it couldn't be used in combat. General Electric, in collaboration with Pratt & Whitney, redesigned the jet engine, but it was Lockheed that perfected the jet engine that was used in the first American operational jet fighter. This military wartime invention was transitioned to the private sector, such that by 1953, the jet engine was used by commercial airplanes like the Boeing 707 and Douglas DC-8.

The Pressurized Cabin

This invention allowed pilots to fly at high altitude without an oxygen mask. The first plane with pressurized cabin was the B-29 Superfortress introduced by the U.S. in 1944. This invention was perfected and used in air transportation by passenger planes.

Radar

Based on Heinrich Hertz's discovery, proving that radio waves are reflected by hard objects, British scientists developed Range and Direction Finding (RDF) technology for airplane detection. RDF provided an early warning and allowed Britain to detect incoming German bombers. The U.S. renamed the technology "RADAR" that stands for Radio Detection and Ranging. The development of the cavity magnetron by Bell Telephone Laboratories in 1940 allowed for increased accuracy and smaller size of Radar systems. These improvements allowed Allies to install Radar on planes. Radar systems are used today in many different applications by the civilian and military.

Radio Navigation

During WWII Robert Dippy developed Gee-H, a radio-based navigation system, which was designed to be used by for more than one plane at the same time. Gee-H was deployed on bombers to guide them when flying into enemy territory and to locate targets. The system did not have any broadcast subsystem required to be on board of the plane. An oscilloscope on board the plane receiving signals from three ground sources allowed the plane's crew to calculate location of the plane. After the war, Dippy worked on a Long Range Navigation (LORAN) system that used similar principles to those implemented in Gee-H system. LORAN was used until it was replaced by GPS.

Cryptographic device

Enigma and Lorentz devices were developed by Germans to encrypt and decrypt the communications among the troops. Colossus was the first computer that could be programmed and used to decode German communications. The technology used in this computer was used later for the development of modern computers.

Atomic bomb

Potential nuclear development and threats of Axis powers was a large concern for the U.S. in 1940. The Manhattan Project started in 1942 to develop the atomic bomb and involved more than thirty research facilities throughout the U.S. The two atomic bombs were built in Los Alamos. The atomic bomb was a significant scientific discovery and became the foundation for the nuclear energy development.

V-2

The V-2 guided intercontinental ballistic missile developed by Germany was the groundwork for later development of modern rockets, satellite communications, and the development of GPS.

Some other top inventions and discoveries during the WWII were penicillin, synthetic oil and rubber, laser, the dynamo-powered torch, and the Jerrycan—most of them still available today (Finnamore, 2015).

Research and development discoveries during the war, along with technologies generated during that period, would not make up for the loss of so many lives. However, significant losses were a key driver behind development efforts, motivating continued commitment and investment in both private and government sectors. Another positive, long-term aspect of the research effort completed during that period of time constituted the foundation for many technologies developed during the post-cold war and many that we still use today.

GPS space-based positioning system was another successful DOD program that started in 1973. Military requirements that triggered DOD development and deployment of GPS included 24 hour and all-weather-conditions navigation, and worldwide positioning capability. GPS technology was based on advanced rapid development in electronic systems, artificial satellite development, radio frequency generators improved equipment, and the atomic frequency standards. The satellites that are part of the GPS constellation are networked together providing worldwide coverage for military and civilian users with GPS equipment.

This innovative GPS communications technology has had a similar impact on the user community as has the World Wide Web (WWW). The breadth of application of GPS technology has implications in domains such as aerospace, transportation, space, etc.

D. SUCCESSFUL R&D ON FAILED PROJECTS

There are many examples and instances where failed/canceled programs produce successful R&D. One such example is the Army Comanche helicopter program. It is a great example of failure regarding the overall intended system output, yet successful due to its quality R&D and R&D's associated outputs. The Comanche, deemed a failure due to cancellation and perceived loss of billions of dollars associated with system development, was able to extend many positive outputs from its conducted/sunk R&D and resultant prototyping. Resources, personnel, and more specifically, the Portable Maintenance Aid (PMA) used to conduct vehicle maintenance were all extended to other Army Aviation platforms. The PMA is currently in use on the Army's unmanned Gray Eagle platform, although it has experienced many iterations of improvement and increased capability since its Comanche days.

III. DOD R&D BUDGET ANALYSIS

This chapter will present an analysis of DOD R&D budgets since the onset of WWII. Overall, DOD R&D budgets, over the last 75 years, have followed a predictable pattern. As the U.S. approaches the beginning of conflict engagement (WWII, Cold War, Vietnam War, OIF, OEF), DOD R&D budgets increase. During times of long drawn out wars (Cold War, Vietnam War), the DOD R&D budgets remain stagnant or decrease. The 1980s Reagan military build-up is one of the few identifiable reasons for an increase in DOD R&D without foreseeable conflict engagement. Figure 1 is used to conduct budget analysis from years 1935–1985.

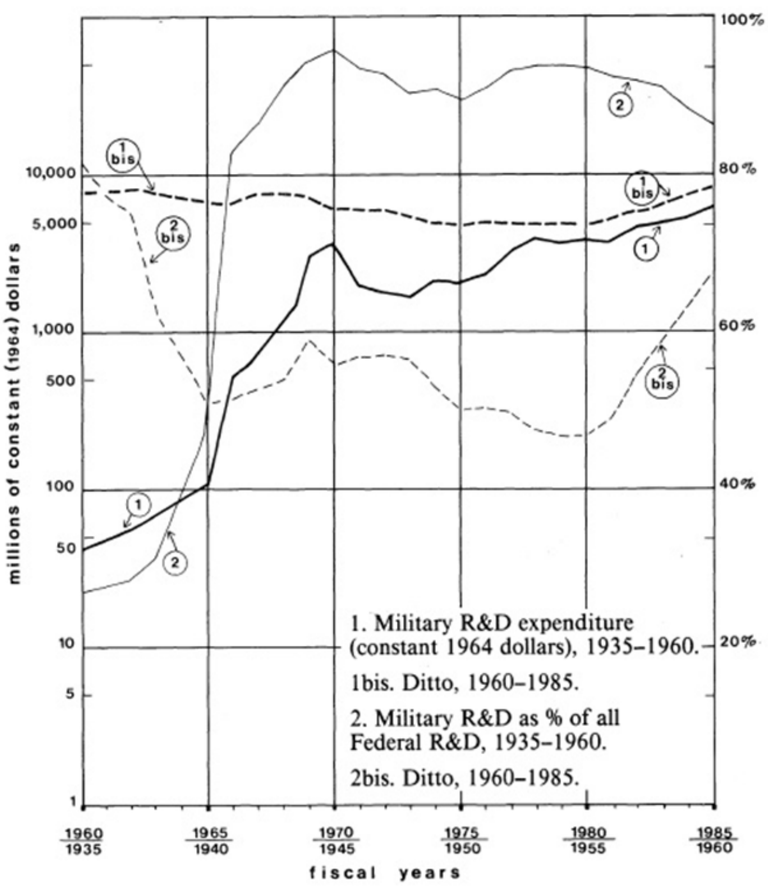

Figure 1. U.S. Military Expenditures, 1935–1985. Source: Forman (1987)

A. ANALYSIS OF U.S. MILITARY R&D EXPENDITURES

1935–1940 showed a steady growth in military R&D expenditures. The growth was fairly linear throughout the five-year period, doubling from $50M to $100M by 1940. WWII had started, but the U.S. hadn't become a direct participant in the conflict yet: "In FY38, the total U.S. budget for military research and development was $23M and represented only 30% of all federal R&D" (Forman, 1987). This was essentially the last year before the U.S. placed increased emphasis on and more funding toward R&D.

1940–1945 showed a sharp increase, rising from $100M to approximately $4B. This coincided with the expanding conflict in WWII, and the U.S.' direct involvement. Within this five-year period, the OSRD was formed (1941) and were afforded essentially unlimited resources. The Manhattan Project, bomb, guided missile, and radar were a few examples of the projects being researched and executed within the OSRD. In 1945, the Military R&D budget took a substantial dip from $4B to $2.5B due to the end of WWII and the death of President Roosevelt.

During this five-year period, military R&D shot up to about 95% of the U.S.' total R&D budget. Military R&D hovered around 80% of the total U.S. R&D budget until about 1960.

1945–1950 showed decline, yet the budget allocation for R&D was still relatively high compared to its peak in 1945. The budget continued its decline for the next few years, but had an uptick in 1949 and 1950. This uptick correlated to the onset of the Cold War. Toward the end of this period, the U.S. was able to determine through its intelligence gathering that the Russia was able to develop their own nuclear capability. The U.S. and Russia were allies during WWII, but neither side trusted the other. The secrecy of the U.S.' R&D efforts may have worked too well, in that the Russia immediately lost whatever trust they had with the U.S. after the deployment of the atomic bomb over Hiroshima. General Patton wanted to extend the conflict to take out the Russian Red Army at the conclusion of WWII. The animosity between both the U.S. and Russia led to the U.S. continuing to allocate R&D funding to bolster National Security in case of pending post-WWII conflict.

1950–1960 showed continued upward growth in terms of dollar allocation. With the U.S. entering the Korean War at the start of the decade, the increasing threat of Russia, the onset of the Cold War, and the United States' devotion to continue to assure militaristic success and national defense/security served as motivators to continue the uptick of R&D investments. The Mutually Assured Destruction Doctrine between the U.S. and Russia may have helped prevent the usage of nuclear warhead capabilities, but it certainly required both countries to invest heavily in nuclear research, programs, resources to deploy and detonate the weapons, and facility security. The allocation of dollars exceeded those from the peak of U.S. involvement in WWII in 1944–1945.

1960–1990 showed the U.S. maintaining DOD R&D budgets above the $5B mark for this 30 year period. There was a downward trend in the early 1960s that changed course with a five-year uptick due to the perceived threat associated with the U.S. sending more troops to Vietnam, resulting specifically from the Gulf of Tonkin incident. During the 1970s, DOD R&D had a downward trend. Multiple presidential administrations and a vocalized disapproval from the American people regarding the U.S. conflict with Vietnam forced the government's hand to scale back DOD budgets to levels lower than it had been the previous 20 years. The R&D budget had a sharp uptick from 1980–1985 under President Reagan's administration. Reagan had a fundamental belief that aligned with the Republican mindset with respect to small government and minimal spending, yet under his Presidency, federal R&D increased along with DOD R&D, with significantly higher increases on the DOD R&D side. In 1981, federal R&D and DOD R&D were relatively equal in dollar allocation ($15B and $17B respectively). By the end of 1988, federal R&D increased to approximately $18B, while DOD R&D increased to $46B (Garfield,1987).

1990–2000 started with a reduction in DOD R&D, while federal R&D continued to increase, illustrated in Figure 2. DOD R&D reductions began just before the Gulf War started in 1990. While the conflict lasted six months, the immediate decline and relative flat line of DOD R&D budgets throughout the decade coincided with military deployment in many different locations around the world for missions to dissolve ethnic cleansing to peace keeping. In 1996, the overall DOD budget was 40% lower than it was in 1985 (Wooley, 2006). DOD R&D spending tends to decrease while the U.S. is not engaged in active conflict. Overall, federal R&D spending remained stagnant and flat together with DOD R&D. Figure 2 also shows American Recovery and Reinvestment Act (ARRA) dollars for both defense and non-defense dollars.

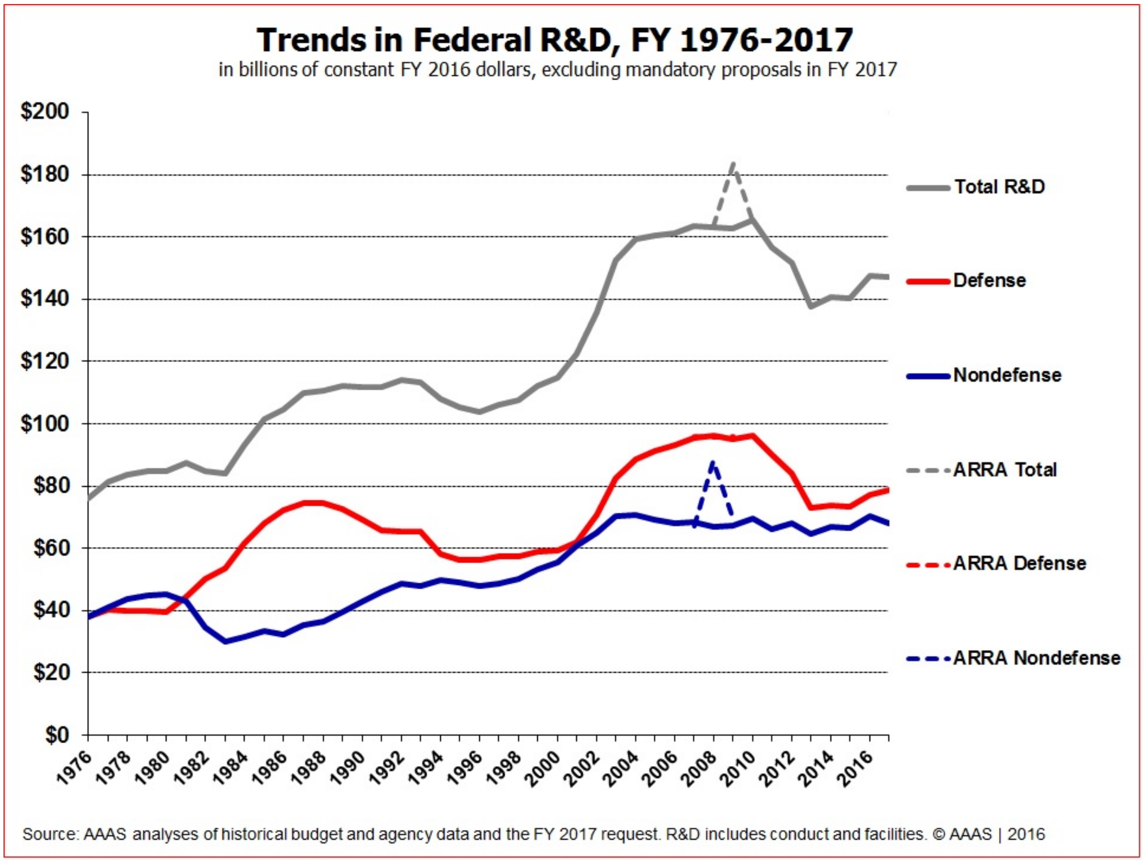

Figure 2. Federal R&D Trends. Source: AAAS (2016), http://www.aaas.org/page/historical-trends-federal-rd.

2000–2016 experienced a significant increase in R&D spending, as the overall DOD budget increased due to the 9/11 terror attacks. DOD R&D spending increased in 2002 in response to the attack, with intentions of beginning an offensive conflict with Iraq and Afghanistan. Both the DOD R&D budget and the overall DOD budget increased significantly just before and after the start of Middle East operations, which began in 2003. The DOD budget went from $328B in 2002 to its peak in 2006 at $535B (Infoplease.com. Source: Center for Defense Information). The spending directly associated with the war efforts (GWOT (Global War On Terrorism) and OCO (Overseas Contingency Operations) dollars) aren't even included in these numbers. The GWOT/OCO dollars had requirements associated with their spending, specifically disallowing the funds to be used for R&D. The funds were for direct support of the war effort, and intended for procurement and Operating and Support (O&S) purposes. DOD R&D surged to unprecedented heights, peaking at about $95B in 2010 just before the initial drawdowns in Iraq.

This 16-year period continues to show the pattern that has been identified in previously analyzed periods. DOD R&D becomes re-invigorated in the years preceding the onset of U.S. participation in conflict/war. During this period, it reached and hovered around the $95B mark until 2010, which coincided with the initial war drawdown in Iraq. The DOD R&D budget decreased to levels that were still higher than they were, then achieved historic peaks in the mid-1980s. Based on this trend, one could predict that the current DOD R&D funding baseline will remain relatively stagnant until the next anticipated conflict occurs. One could even predict that if there is a sudden surge in the DOD R&D budget, the U.S. is likely to engage in conflict within 2–3 years.

B. ASSOCIATIONS BETWEEN R&D AND GDP

As shown in Figure 3, the United States has experienced significant, consistent growth over the last 75 years. Throughout each decade, the net result has been positive growth with some low spots or negative growth sprinkled throughout. The growth may not be year-over-year growth, but growth nonetheless.

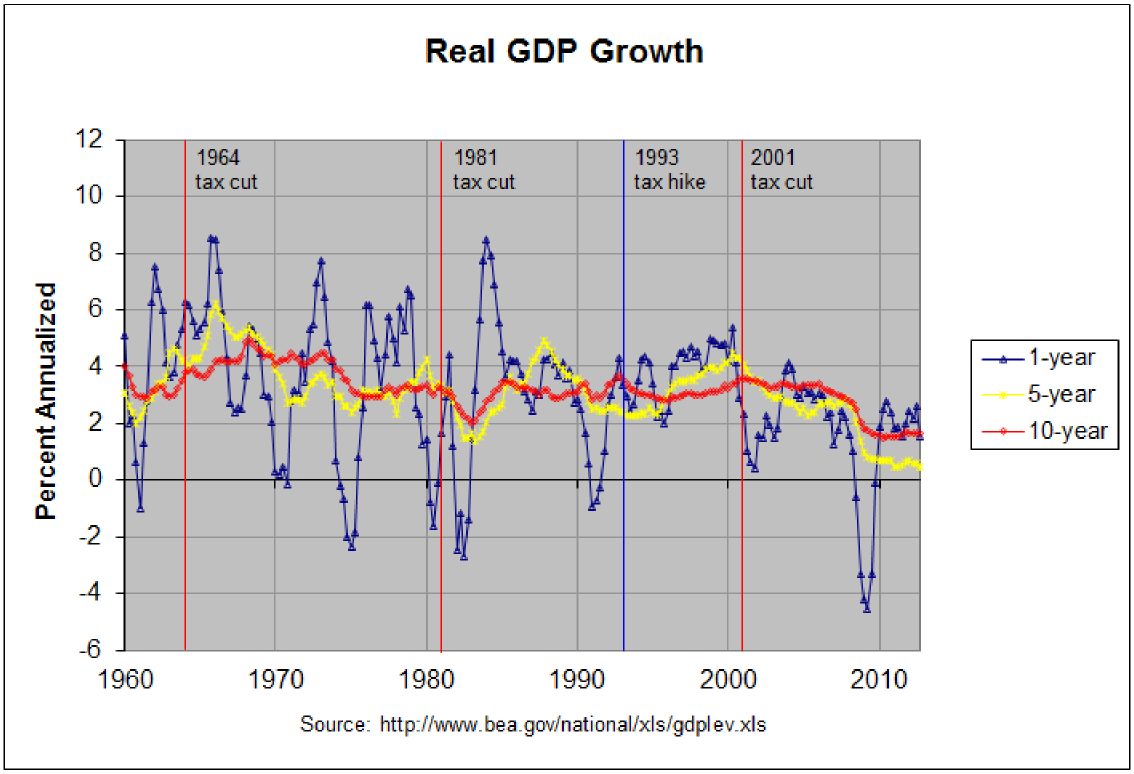

Figure 3. Real GDP Growth. Source: Bureau of Economic Analysis (n.d.), http://www.bea.gov/national/xls/gdplev.xls.

The early 1940s showed double digit increases in GDP year after year for the first four years of the decade. This corresponds to the buildup in defense resources and the U.S. participation in WWII. For three years following the conclusion of WWII, the GDP decreased due to a decrease in defense spending and an inflation rate of over 18% (Amadeo, 2016a). The next 20 years showed consistent, steady growth, in which only two years did not experience growth, and those years were both less than 1% negative growth. The worst eight-year period was 1974–1982, in which it experienced four years of negative growth. During this timeframe, DOD spending was cut and left flat during the Carter Administration. Conversely, under the Reagan administration, GDP growth was no less than 3.5% each year. This coincided with Reagan's Star Wars initiative, military buildup, and increases in R&D. The period 1990–2007 experienced consistent growth under Clinton and Bush.

With peace time under Clinton, and emphasis on the War on Terror under Bush, there aren’t significant spikes or lulls to reflect a change in GDP with respect to increases in military spending and investments in R&D. During WWII and the increased military spending in the 1980s, there were sizable increases in GDP growth. But this appears to be simply correlation, as throughout this 75-year period, through periods of active conflict, preparation to engage in conflict, and peace time, GDP does notincrease or decrease respective to DOD spending and associated increases in DOD R&D expenditures. GDP grew and fell many times at differing slopes relative to DOD R&D allocation and investments. GDP sensitivities seem to be more related to the economy, recessions, and singular events.

What about correlation/causation from the other perspective? Does output from R&D impact GDP? The simple answer is yes; successes realized and gained from R&D do translate to economic growth. Significant discoveries and innovations, such as the transistor, GPS, ARPANET, and nuclear fission/fusion clearly increased human efficiencies and provided economic growth for the United States and foreign countries. The direct and indirect impacts aren’t defined and metricized. There’s an understanding that these types of discoveries have unquantifiable impacts on the population and a non-metricized Return on Investment (ROI). Governments and corporations partake in R&D to reap the benefits of both direct and indirect discoveries and successes, knowing that outputs from these investments may not be realized in the short term.

C. DOD R&D PERCENTAGES RELATIVE TO OVERALL FEDERAL R&D

The U.S. began devoting significant attention and applied funding toward the general notion of R&D in the late 1930s. At the same time the U.S. was preparing to enter WWII, it was also investing R&D dollars to support foreign led, non-militaristic research initiatives. From the early 1930s to 1940, DOD R&D encompassed just under a third of the overall federal R&D budget (Figure 3). From 1940–1960, DOD R&D surged to and remained at approximately 90% of the total federal R&D budget (Figure 3). The DOD R&D budget remained a high percentage of the federal R&D budget for such a long period of time due primarily to WWII and the lingering distrust of Russia, leading to the onset of the Cold War.

During the 1960s, the overall R&D percentages shifted in favor of federal R&D, as there was renewed interest during this time to invest research into non-defense entities and ideas. DOD R&D and federal R&D marched forward at an even pace for the next 20 years until 1980. President Carter's defense cuts kept the DOD R&D budget lower and flat during the 1970s than in previous years, causing the DOD R&D budget to remain in line with the federal R&D budget.

Following the conclusion of the Vietnam War, the 1980s ushered in a new mentality to revitalize the U.S. The Reagan administration allocated more dollars toward the rebuilding of the military. Not only were the defense budgets higher, in order to directly combat "low morale, low pay, outdated equipment, and practically zero maintenance on what did exist," ("Ronald Reagan's Military Buildup," n.d.), Reagan also invested heavily into defense research. Under Reagan, a research program called "Star Wars" was hatched to defend the U.S. against Russian nuclear warheads utilizing a system that was resident in space. Not only was it a futuristic research project, but it helped the U.S. "circumvent the UN's Anti-Ballistic (ABM) Treaty" by having the defense system not resident on Earth ("Ronald Reagan's Military Buildup," n.d.). As Reagan ended his second presidential term in 1989, he left with a military budget "43% higher than the total expenditure during the height of the Vietnam War" ("Ronald Reagan's Military Buildup, n.d.). Reagan was able to increase defense spending without directly impacting a fragile economy, as the expenditures sent the U.S. into even more significant debt. However, the investments made in research during the 1980s have attributed to technological advancements and capability currently being employed by the military in 2016.

As Reagan increased military budgets, allowing for DOD R&D budgets to increase, the federal R&D budget suffered from a dramatic decrease to start the 1980s, but had a consistent increase from 1983 through the early 1990s. In 1987, the DOD R&D budget under Reagan peaked at around $75B. During this same time, federal R&D was in the midst of its own growth period, but still lagged behind the DOD R&D budget. The DOD R&D budget occupied almost 70% of the overall U.S. R&D budget.

After a flat period for a couple of years during the Gulf War, the DOD R&D budget encountered a steady decline followed by a flat line for the remainder of the 1990s under the Clinton administration. After the 9/11 attacks on the U.S., the percentage of DOD R&D soared and accounted for approximately 60% of U.S. R&D by 2007. The percentage would have been higher, but the federal R&D grew at a similar rate from 1996–2003, and flat lined during the DOD R&D growth as the U.S. entered into conflict with Iraq and Afghanistan. DOD R&D has dropped sharply since the Iraq drawdown. Since 2012, DOD R&D has been flat, accounting for just over 50% of overall R&D.

In summary, DOD R&D budgets have accounted for more than 50% of the overall research budgets since 1940, with the exception of a 2–3 year window in the late 1970s, where federal R&D spending exceeded that of the defense department. During the short amount of time that federal R&D spending actually exceeded DOD R&D spending, the federal R&D budget was less than 10% higher. The emphasis has always been on DOD R&D due to military benefits, national security benefits, and the historical ability to extend discoveries and successes to both the U.S. and the world populace.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. GPS CASE STUDY ANALYSIS

As successful as GPS has been on both the battlefield and in worldwide civilian life, the end state wasn't realized when the idea of GPS was identified as something needed to transition from concept to capability. This section will be prefaced by an overview, followed by analysis to the following questions/statements:

- Why was GPS technology developed?
- What was the military's first application of satellite communication?
- What prior research was conducted to help mature the GPS system?
- What other technologies did the military benefit from due to GPS?
- What are the benefits to GPS outside of the military?
- What are the economic benefits to GPS?
- How GPS demonstrates DOD R&D's ability/adeptness to adapt to paradigm shifts.

These analysis questions will directly answer the secondary research questions presented in the introduction of this research.

A. OVERVIEW

"The Global Positioning System (GPS) is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services" (Gov, G. P. S. 2012). GPS is a constellation of network satellites that constitutes the space segment of the GPS system. Currently, there are 31 GPS satellites flying in the medium Earth orbit; 24 of them are active and considered part of the core operational GPS constellation. These satellites are orbiting the earth at an altitude of over 12,000 miles. The GPS satellites are controlled and monitored by 17 ground facilities networked together and located throughout the world. The last segment of the GPS system is the User segment that includes the user community and equipment used to communicate with the satellites by receiving the signals and calculating the user's position. The user community who are receiving the critical positioning information are both civilian and military users around the world. (Gps.gov, 2012).

B. WHY WAS GPS DEVELOPED?

The notion of GPS was not conceived during a round table discussion of good ideas to focus on and devote research toward developing an end state solution to benefit U.S. soldiers. Actually, it happened almost by accident. In 1957, two physicists at the Johns Hopkins Applied Physics Lab (APL) (a laboratory under the Office of Scientific Research and Development focused on military research) decided to test whether they could detect the emission of microwave signals from the recently launched Russian Sputnik satellite. Fortunately, due to the heavily competitive technological landscapes between Russia and the U.S., Russia launched the Sputnik with a regularly emitting signal to provide proof that their satellite was, in fact, in orbit (Johnson, 2010b). These two APL physicists quickly realized they could obtain a heartbeat signature from the satellite while it was in orbit in space. As they started recording the frequency of signals originating from the Sputnik, they realized that the associated time signature wasn't consistent (Johnson, 2010b). They successfully utilized the Doppler Effect to determine the entire Sputnik orbit pattern. This was the first iteration of GPS, as they learned and demonstrated the use of a ground receiver to determine the location of a satellite.

The next iteration of GPS occurred shortly after this discovery was made. The two physicists' supervisor asked if they could determine the opposite of what they just demonstrated. Can the satellite determine the location of an object on Earth? After a quick confirmation that yes, the bi-directional discovery of space and earth objects could identify each other's locations via signals from the satellite, the first direct application/ requirement for militarized use of GPS was born (Johnson, 2010b).

C. THE FIRST MILITARY APPLICATION OF GPS

The military had growing interest in tracking and guiding munitions and missiles using satellite guided positioning. Leveraging the new discovery of tracking these weapons via satellite was intriguing. The specific use case that helped transition the notion of tracking objects via satellites to our current instantiation of GPS involved launching missiles from mobile submarines. Due to the constant changes in location, launching missiles from submarines was difficult, if not impossible, in the late 1950s. With this requirement, research began to develop the system of satellites and ground stations/receivers to identify positions of objects on earth.

Less than 3 years after the raw discovery of satellite communication, the research transitioned to a Navy Program of Record called Transit in 1959 (Sullivan, 2012). The program initially launched 6 satellites into orbit to provide navigational intelligence to Navy Polaris submarines. Due to the circumference of the Earth being larger than the range of 6 satellites in orbit, the satellite population was increased to 10.

D. PRIOR RESEARCH EFFORTS LEADING TO THE DEVELOPMENT OF GPS

Prior to 1973, when GPS design and deployment began, there were years of studies and research that produced different experimental positioning and navigation systems that constitute the foundation for current GPS system.

In the past, primitive tribes and mariners used celestial-based positioning techniques for navigation. They used angular measurements of the stars to guide them during travel. The magnetic compass was another practical instrument used in the past for orientation by sea navigators.

After radio frequency generators became available, The Massachusetts Institute of Technology developed and tested a navigational system that had increased accuracy and a range of approximately 1500 miles. In 1943, U.S. Navy took over the project, and the Long Range Navigation (LORAN) program was born. The all-weather LORAN-A system was deployed in Europe and North Africa in 1944 with the main goal of providing long distance radio navigation support to U.S. forces and its Allies. The system was extremely useful during night bombing operations. Throughout the years, both the government and private companies joined forces and improved the LORAN system’s technical capabilities. By 1962, a new version of the system, LORAN-C, became the only long range navigational system that was compliant with the international requirements of the time (Jansky & Bailey 1962). In 1974, civilians were permitted to use LORAN-C capabilities.

The Decca Navigator System was another long range radio navigation system developed during World War II. This system was installed in military and civilian aircrafts, ships, and boats allowing them to locate their position (Jansky & Bailey 1962).

The development of Line-of-Site (LOS) communications systems allowed researchers to study and assess new alternatives for navigation aid capabilities. Between 1959 and 1960, the Navy had requirements to locate ballistic missile submarines and ships, while the Air Force was seeking to develop a radio navigation system to guide their Minuteman missiles. Transit was the first low-altitude satellite navigation system developed by the Navy in 1960. The Transit constellation had only six satellites and a few ground stations. Transit system had several drawbacks, however: it was very slow, it took a long time to receive a signal from the satellite, and it could not be used for high-speed platforms. Timation was the follow up satellite development created by the Naval Research Lab, in 1967, where high-stability clocks and 2D navigation were provisioned with each Timation satellite (Sullivan, 2012).

This development was based on the scientific discoveries made after the launch of Sputnik satellite and Doppler Effect theory. The studies and the research performed for the development of the TRANSIT system set the stage for future GPS systems.

During the same time period, the Army worked independently in developing the same/similar satellite- based radio navigation and positioning capability. In 1964, the first Sequential Correlation of Range (SECOR) satellite was launched. By the end of 1966, eight SECOR navigation satellites were launched by the Army (Nichols, 1974).

In 1963, the DOD requested Aerospace Corporation to perform studies for defining space capabilities and applications to meet national defense needs. In the same year, the Air Force initiated research in developing technologies needed to determine the location of aircrafts. Later, this effort became known as the System 621B program. Research performed by the Aerospace Corporation caught the attention of the Air Force, which worked on 3D navigation system and pseudorandom noise (PRN) technologies that were part of the System 621B program. The research results and techniques developed by Aerospace were used within this System 621B design (Pace et al.,1995).

All disjointed activities pertaining to the development of satellite navigation systems performed by the Army, Navy, and Air Force had the same objectives and goals, but unfortunately, no joint requirements. In 1968, the DOD created the Navigation Satellite Executive Group (NAVSEG). NAVSEG was tasked by the DOD to define the requirements for the new satellite navigation system and to define the new design for the satellite constellation and ground stations infrastructure. In 1973, DOD approved the development of NAVSTAR Global Positioning System in a three-phased approach (Pace et al., 1995).

It took 16 years of research activities, prototyping and development from all three DOD Services and industry partners to finalize the satellite-location mapping system design that included the technical characteristics and features required by the military. Achieving such a remarkable development was possible due to the DOD’s financial commitment to invest in positioning and navigation research and development throughout all these years. The DOD’s consistency and focus allowed the various entities and research groups to leverage emerging tools and information from their independent efforts – even though not always collaboratively—to challenge existing capabilities and continue an aggressive approach to build on the industry’s efforts, resulting in new capabilities and applications (Pace et al., 1995).

E. GPS SCHEDULE AND BUDGETS

The Office of the Secretary of Defense (OSD) understood the importance of developing GPS capabilities for the warfighters and provided continuous support throughout all phases of the program. Collaboration among DOD Agencies, FFRDC organizations, and defense contractors was critical in the success of the GPS program.

In 1973, the DOD approved Phase 1 of the NAVSTAR GPS program. The first phase was funded $100 million, and its schedule and execution included the following activities and objectives:

- Finalizing joint requirements and systems’ design

- Development of four satellites
- Development of the launch vehicles
- Construction of a prototype ground satellite facility
- Develop/Test/Implement three types of receivers
- Proof of concept of space navigation system through testing. (Pace et al., 1995).

During 1974 and 1977, two experimental satellites were launched. These two satellites were used for a short period of time for extensive testing. After the DOD successfully demonstrating the use of atomic clocks, spread-spectrum techniques for radio navigation & positioning capabilities, as well as nuclear detonation sensors, the GPS program received approval with the development of Block I satellite development.

However, funding stability for the GPS program became an issue starting in 1980. GPS capabilities and benefits were not well understood by the military during that time since GPS was not then considered a weapon system. The GPS program was forced to reassess the design of the satellite constellation due to budget cuts during FY81 and FY86, when the DOD decided to cut $500 million out of the GPS budget. The redesigned system included only 18 satellites instead of the 24 satellites proposed initially.

The GPS program was also delayed almost two years with the launch of second-generation satellites (Block II) due to a Space Shuttle Challenger accident that happened in 1986. After 1989, twenty-three (23) Block II GPS were launched. By the end of 1995, the GPS constellation consisted of 24 operational satellites (Pace et al., 1995).

F. SUCCESS OF GPS TECHNOLOGY USE DURING WAR

When Operation Desert Shield started in 1990, only 16 GPS satellites (out of 24) were operational. GPS receivers were not available to Army soldiers during that time due to limited availability. Only Army reconnaissance units and unit commanders were furnished GPS receivers. Special Operations groups used this technology prior to the beginning of this war and they knew how valuable it was especially in drab desert environment. The Army quickly realized how important GPS technology was for deployed forces and did their best equipping as many units as possible with GPS receivers during the conflict. Lieutenant General Frederick Franks, the VII Corps Commander, stated “They [(GPS receivers)] were invaluable in avoiding fratricide and allowing accurate navigation and artillery fires” (Dissinger, 2008).

During the conflict, GPS was used by the military in precision weapon delivery, help in landing aircraft on improvised fields, positioning troops, among many others. GPS capabilities were critical in helping the U.S. warfighters and U.S. Allies to win the conflict in just four days.

G. WHAT ARE THE IMPLICATIONS OF GPS SUCCESSES RESULTANT FROM R&D INVESTMENTS?

1. The Compounding Military Benefit

With the launch of Sputnik in 1957, the floodgates opened for associated research, development, and production activities to field a satellite based system that could orbit earth and communicate with receivers on earth. The resultant advancements in technology went beyond the scope of just a satellite architecture. The results were compounded, with both the U.S. military and civilians reaping benefit. In this specific case, worldwide civilian life has also reaped the benefit. The subsequent paragraphs will discuss some of the secondary impacts of a singular discovery, which supports the importance of continued future emphasis on R&D and defending R&D in times of budget cuts and fiscal uncertainty.

The development of the satellites themselves had to go through multiple design iterations. The original design utilized requirements to integrate with a Thor-Ablestar rocket. The integration/collaboration between rocket and satellite were the first of its kind in the U.S.. With a rocket failure occurring on Transit 1 in 1959, it was renamed to Transit 1A, as Transit 1B had a successful launch in 1960 (“Transit Satellite,” *Wikipedia*, n.d.). As more Transit satellites were launched into orbit, they were continuously refined with increased capability. The refinement and continuous testing paved the way for today’s reliable and highly capable satellites.

As the satellite technology was being developed at APL, rocket technology experienced rapid growth, as it had a significant forcing function as an enabler for satellites. The Thor-Ablestar rocket experienced failure with Transit 1A, but was quickly modified to compensate for the experienced failures. In less than a year, the Transit 1B was successfully launched via the improved Thor-Ablestar (The JHU Gazette Satellites, Rockets, and More, 2010). Even with success, the Thor rocket was used as a short term means to launch and demonstrate satellite communication technology. Upon successful completion of the testing and proof of concept through 1965, the Thor-Ablestar was replaced by the Scout rocket as the long term solution to launch Transit satellites.

With the utilization of the mature Scout rocket, the Transit satellite had to endure a re-design in order to integrate with the Scout, specifically regarding shedding Transit weight and replacing some electrical components that had little susceptibility to enduring damage from vibration ("Transit Satellite," *Wikipedia*, n.d.). As the rocket technology matured, the satellite technology needed to catch up, forcing refinements that gained fabrication and endurance efficiencies. Aside from the enhancements associated with rocket integration, each Transit launch leveraged on lessons learned from the previous launch. As confidence grew, they increased the capability and troubleshot problems. With each launch, different classified payloads would be attached to the satellite as extended/ new capability was tested. These back and forth forcing functions directly impacted the rapid maturation of these technologies throughout the 1960s and 1970s.

ARPA, later known as DARPA, was created in 1958 in direct response to the Russian launch of the Sputnik. One of ARPA's first projects was the development of Transit with the APL. Due to both ARPA's and APL's proper level of funding and resource allocation, these organizations were able to conduct proof of concept testing, and extend concepts to real world testing. More importantly, these organizations were afforded the opportunity to test emerging technology with the notion that failure will assist in progress, rather than serving as a hindrance. These organizations were not threatened by failure. The early successes associated with the Transit program helped reinforce the solid decision in standing up the ARPA organization. Without this program, and an upfront injection of confidence regarding immediate successful R&D, one could ponder whether ARPA would have withstood the test of time and opportunity to defend its reason for being. Today's federal R&D faces heavy public scrutiny for publicized failures regarding high visibility initiatives. There's little tolerance or patience for failure.

As Transit approached the 1970s, it was embraced by all branches of the military and renamed NAVSTAR (Sullivan, 2012). From a military perspective, one of the large successes of NAVSTAR was the joint deployed nature of the system, in that all of the joint forces could utilize the technology. This is a significant victory in terms of cross platform interoperability, lack of proprietary nature, and cost sharing, allowing for widespread adoption of the technology.

As evolution continued into the 1980s, NAVSTAR, which was formally renamed GPS, increased the satellite footprint to 24 satellites. As these new satellites were launched into orbit, other R&D efforts were able to leverage the success of the GPS infrastructure. The atomic clock and a sensor array capable of detecting the launch of nuclear weapons were co-located payloads on the latter launched satellites (Sullivan, 2012).

The military has extended its use of GPS and satellite communication to modern day technology on the battlefield. Command and control of UAVs, like the Army's Gray Eagle, occurs via satellites, allowing for global, non-line of sight operations. These same UAVs also rely on GPS for autonomous flight behaviors and return to home procedures. GPS also "steers" precision guided Joint Direct Attack Munitions (Hallion, 1995). Ground equipment utilizes commercialized Google Maps and proprietary maps to fuse digital imagery with global positioning.

The discovery of today's GPS, through significant R&D and testing, failures, and resultant fixes and re-tests, directly contributed to the iterations of the aforementioned technological areas and organizational creations. Utilizing GPS to understand locations of personnel, air and ground vehicles, or guide munitions on the battlefield is used as a standard today. GPS is an invaluable tool.

2. Benefits Beyond the Military

GPS only became today's instantiation of GPS due to continued R&D throughout the longevity of the Transit program. It evolved throughout that program, throughout the NAVSTAR iteration, and continued evolution to its current GPS state as surrounding technology evolved, more resources were devoted to the ecosystem, and humans designed supporting hardware and software to utilize the infrastructure.

In 1983, President Reagan allowed the use of GPS outside of the military for commercial aircraft (Sullivan, 2012). This extended beyond aviation, and eventually private industry began developing and selling handheld GPS devices. GPS then began spreading beyond domestic U.S. use, rapidly experiencing worldwide adoption. This began the development of civilian applications and adoption of GPS technology.

As GPS was initially developed for enhancing military combat capabilities, Standard Positioning System (SPS) is the GPS service that is available to civilians. Some of the areas where SPS is used include:

- providing Geodetic control
- surveying control for Photogrammetric control surveys and mapping
- identifying offshore drilling location
- surveying of power lines
- mining and mineral exploration
- estimating gravity anomalies using GPS
- assisting in Harbor navigation
- offshore positioning: shipping, offshore platforms, fishing boats etc
- air traffic control
- scientific surveying
- measuring ocean waves and the like. (Raju, n.d.)

With the fusion of digital imagery, maps, and global positioning, the paper map is no longer used for navigational purposes. Handheld GPS receivers, smartphones, and navigational units for automobiles have penetrated the worldwide consumer market for navigation. Beyond navigational purposes, creative entities have created applications and ecosystems predicated on GPS. Geocaching is a game that relies on GPS to find a treasure at specific coordinates. A software application called Pokemon GO utilizes GPS to catch digital creatures on a smartphone. Google even utilizes your smartphone's GPS to passively collect traffic information and monitor when groups of users all decrease speed or cease movement. The results are posted via color coded lines and accurately depict the length of traffic congestion on the map.

The compounding effect of discoveries made resultant from sponsored R&D can be extended to the emerging technologies associated with civilian autonomous vehicles, ranging from self-driving cars to air vehicles (drones) used for delivering packages. Google's self-driving car project utilizes sensors and algorithms to keep the car within the standard lanes on a road, but it utilizes GPS to provide the navigational route to travel from origination to destination (Pullen, 2015). Amazon has its own R&D program focused on the development of air vehicles that will deliver packages to customers utilizing GPS coordinates to determine destinations (Lavars, 2015). While both of these technologies utilize GPS as its primary source for navigation, GPS could also be used to monitor the real-time locations of any of these sources of autonomy. Extending the notion of GPS tracking, police departments are utilizing GPS for real-time police vehicle locations (Smith, 2009). When the police department gets a call/request requiring the dispatching of a police officer to rectify the situation, the dispatch utilizes GPS to locate on a map where the call's origination point and fuses that data with the GPS location of the closest officer to gain the greatest efficiency and response time (Smith, 2009).

3. GPS Benefits to the U.S. Economy

Figure 4 represents the U.S.' economic benefit associated with the utilization of GPS for the year 2013. There's both a range and a mid-range value. For the sake of this research, the mid-range value will be referenced. Total economic benefit is $55.8B. The $55.8B depicted here is from industries and sectors where tangible realizations in cost savings or gains in efficiencies can be calculated (Leveson, 2015).

	Application Category	Range of Benefits ($billions)	Mid-range Benefits ($billions)
A	Precision Agriculture — grain*	10.0–17.7	13.7
A	Construction — earthmoving with machine guidance*	2.2–7.7	5.0
A	Surveying	9.8–13.4	11.6
A	Air Transportation	.119–.168	0.1
C	Rail Transportation — positive train control	.010–.100	0.1
C	Maritime Transportation — private-sector use of nautical charts and related marine information*	.106–.263	0.2
A	Fleet vehicle connected telematics*	7.6–16.3	11.9
A	Timing —average of eLoran and GEOs estimates	.025–.050	0.1
A, B	Consumer and Other Non-Fleet Vehicle — average of estimates based on willingness-to-pay and value of time*	7.3–18.9	13.1
	TOTAL	**37.1–74.5**	**55.8**

A = confident, B = indicative, C = notional.
*Includes benefits from purchase input cost savings.
Note: Numbers may not add to totals due to rounding.

Figure 4. GPS Benefits to the U.S. Economy. Source: GPS World (n.d.), http://gpsworld.com/the-economic-benefits-of-gps

There's also intangible benefits to GPS that have been realized. These benefits are difficult or impossible to metricize. For instance, after Transit 4B launched in 1961, analysts soon discovered that the agreed upon location of Hawaii was actually incorrect by approximately 1km (Wade, 1997). Other intangibles to which Return On Investment (ROI) is difficult to calculate include leisure activities, safety, environmental efficiencies, and improved security postures (Leveson, 2015). The $55.8B metric is effective in placing a rolled-up value based on actual cost savings/avoidance metrics, but with the aforementioned intangibles, proves to be a significant underestimate.

GPS technology not only provided the metricized $55.8B of cost savings/ avoidance and benefit, but it also created a new industry within the technology sector. Companies were created devoted to associated GPS hardware and/or software development, jobs were created to support the companies, and governing boards were created to increase capability and ensure the adherence to standards for worldwide consumption. The National Space-Based Positioning, Navigation, and Timing Advisory Board is one such example of a governing body that provides input to DOD, which is the ultimate body that oversees GPS (Leveson, 2015).

These aforementioned successes depict the associated successes of the early investments in continued development, refinement, and maturation of the GPS program. The benefits range from military to civilian, and extend both to metricized costs associated with savings/profit due to utilization of GPS, and also some unquantifiable examples of GPS use cases.

H. ADAPTABILITY TO PARADIGM SHIFTS

A significant foundational reason for the success of GPS does notnecessarily revolve around the technological advancement and maturation process enacted over the last 50 years. The reason lies more within the structure and environment which harvested and fostered the ability to think outside the box and take risks: "APL was a superb environment for inquisitive young kids, and particularly so in the Research Center. It was an environment that encouraged people to think broadly and generally about task problems, and one in which inquisitive kids felt free to follow their curiosity (Johnson, 2010a)."

Within the APL in 1957, the physicists responsible for the Sputnik research were at the onset of a paradigm shift. Leveraging the success from the Sputnik, APL was able to further the technology and apply specific use cases to warrant the continued research of the emerging technology. Had APL not been postured (from a personnel, resource, and funding perspective) to adequately assess and embrace an impending paradigm shift, GPS as we know it today may not have been discovered or implemented. Or maybe it would have occurred, but the technology would not be as robust and mature as it is today. This statement lends itself to the notion that without proper resources, time is lost and unrecoverable. With lost time, the ability to compound and integrate discoveries into other established technologies or other discoveries takes longer to realize, if realization occurs at all.

I. HOW DID THE GPS INITIATIVE FLOURISH AS A PROGRAM UNDER A ROBUST R&D BUDGET?

Robust military R&D allows for cutting-edge technological development that sentries against challengers' surprises; it also helps create equilibrium among current warfighters' technological needs. Robust R&D (through investment) also promotes future stability of U.S. defense requirements and their enhancement.

An analysis regarding what a robust defense R&D budget should entail, and how it applies to the GPS discovery and program development:

- **Predictable R&D funding—**In the mid to late 1950s, DOD R&D was on the uptick (Figure 3). Due to Cold War escalation with Russia, overall DOD budgets and DOD R&D budgets were very stable and predictable as discussed and analyzed in Chapter III.

- **Support from Federally Funded Research and Development Centers (FFRDC) universities and laboratories—**The GPS program was jointly researched, developed, and tested by many different organizations. APL was the main FFRDC involved with the development and execution. Due to the expertise residing in an FFRDC, the knowledge and integration was easily transferrable to other Federal organizations, both research and departments.

- **Cooperation with private sector institutions—**APL had significant private sector relationships, including Douglas and Aerojet for the development of the Thor rocket to send the satellites into space. Likewise, two major primes on the Scout consisted of Thiokol and Aerojet, in conjunction with NASA. GPS experienced a solid combination of utilizing internal expertise, development, and requirements generation along with the technical prowess of private corporations to integrate components into a system of systems.

- **Well-equipped defense laboratories—**Naval Research Laboratory was a large influence in the success of the GPS development and deployment. Allegany Ballistics Laboratory, originally founded during WWII as a laboratory underneath the Office of Scientific Research and Development. This rocket development lab was transferred in 1956 to Naval Sea Systems Command ("Allegany Ballistics Laboratory," *Wikipedia*, n.d). Again, the GPS demonstrates solid collaboration between different defense laboratories to solve problems.

- **Technological know-how, and the world-class engineering expertise and skills of personnel supporting R&D projects—**APL had many young, talented physicists, scientists, and engineers. The two scientists who discovered Sputnik's radio frequencies were both pursuing technical doctorate degrees. These doctorate degrees furthered APL's world-class knowledge and resources, gaining a SME in specific areas. APL was properly positioned to hire talented individuals who had some freedom and flexibility to conduct research in areas of interest. (United States Congress. Office of Technology Assessment, 1992).

APL was positioned nicely to be able to both have the appropriate resources to make new discoveries, and to also be able to execute and further explore those discoveries.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSION AND RECOMMENDATION

The U.S. is currently postured with many different DOD R&D centers throughout the country, focusing on both military applications and civilian applications. These R&D centers are actively solving difficult problems, and are also well positioned to quickly react to emerging/sudden problems, such as vaccines for Ebola and Zika (Pellerin, 2014). It is critical for the U.S. to continue to emphasize the importance of R&D, especially in times of fiscal uncertainty requiring budget cuts. It is imperative that these facilities are funded adequately and able to maintain their R&D core competencies, intellectual base, technical skills, laboratory infrastructure, etc., to respond quickly and effectively to such unexpected technological threats, and thus continue to support the DOD research efforts. Today's problems ranging from advancements in technology to battlefield enhancements of weapon systems to medical vaccinations are all beneficiaries of yesterday's research. Future research is predicated on lessons learned and the ability to leverage both success and failure.

A. SECONDARY RESEARCH QUESTIONS ANSWERED

This research has presented both background and analysis to help understand, defend, and answer the primary research question. Let's revisit the secondary questions.

1. What R&D Organizations Were in Place to Successfully Develop the GPS System that We Know Today?

After 1960, the Air Force and Navy realized the need for developing a global navigation and positioning system. The two agencies had different mission requirements and chose independent approaches in developing this task. Both agencies used the existing DOD R&D laboratories, FFRDC facilities, and staff researchers to perform studies and develop concepts/prototypes for developing a radio navigation system.

The Navy funded Naval Research Laboratory (NRL), ARPA, and Johns Hopkins Applied Physics Laboratory for the development of two satellite navigation systems named Transit and Timation. Using the existing facilities and existing intellectual property was a great benefit for the Navy and helped speed up the process of developing and launching the first Transit satellite constellation in less than seven years.

In 1963, the U.S. Air Force sponsored Space and Missile Systems Organization (SAMSO) and Aerospace Corporation in performing research on a navigation system that later became known as System 621B program. Both were experienced organizations that performed research in the past for subsystems that could be integrated within the satellite navigation system. The exiting Air Force test facility, White Sands Proving Ground located in New Mexico, allowed researchers to perform simulations and extensive testing for the System 621B program. Having the technical expertise and facilities available for assessing different solutions allowed the Air Force to prove and develop techniques such as three-dimensional navigation, pseudorandom noise, etc., that were integrated into the GPS system.

In 1973, the Air Force was designated by DOD as the lead Agency responsible for coordinating all GPS activities. It was established that a Joint Program Office (JPO) will develop the GPS system with the support of all DOD Agencies. Space and Missile Systems Organization was chosen to host the JPO's development of the GPS system. The Air Force coordinated the availability of DOD R&D and FFRDC facilities and participation of scientists supporting GPS development. DOD personnel along with defense contractors worked toward finalizing the joint baseline requirements for the GPS system and combined the research performed for the TRANSIT, Timation, and System 621B projects for final design and development of the GPS constellation. The successful execution of the GPS program, from the inception until full operational capability, was the result of strong collaboration between all Agencies and the support and experience of organizations such as NRL, ARPA, SAMSO, and APL.

The successful development of the GPS system shows the importance of maintaining defense R&D laboratories and FFRDC organizations involved in DOD programs. The experience and expertise acquired by these organizations is irreplaceable for future defense activities.

2. What Budgets and Schedules Influenced the GPS Development?

After the development and launch of the GPS Block I satellites, the GPS program encountered a budget cut of almost 30%. Such budget cuts impacted phase II of the program that included the development of the GPS Block II satellites. Understanding that a space-based worldwide navigation system is a critical capability for the military, JPO along with the support organizations and DOD Agencies were able to re-scope the program and redesign the entire system allowing the program to continue.

The program also encountered a holdup in 1986, when the JPO did not have a launch vehicle for GPS satellites due to the Challenger accident. JPO found an alternative avenue by redesigning the Block II satellites to be compatible with Delta II launch vehicles and resumed the launch of phase II satellites.

JPO, as a program and system integrator, had a clear and consistent vision in developing the GPS system. JPO was able to overcome the technical challenges, addressing and mitigating risks, by working closely with all Agencies and support contractors to identify optimal solutions through research, studies, lab and field testing, thus reaching the GPS system's full operational capability in 1995.

3. What are the Implications of GPS Successes Resultant from R&D Investments?

The benefits that humanity has received due to the creation and development of GPS are both quantifiable and unquantifiable. In 2013, an estimate, just based on measured U.S. productivity resultant from the use of GPS, is $55.8B. Software applications like Google Maps or Pokemon GO are difficult to quantify due to a lack of standardized metric associated with personal gains in efficiency or pleasure. The benefits extend far beyond the intended militaristic applications back in the 1960s and 1970s, in that GPS is used for flight autonomy for UAVs and ground vehicles, precision guided munitions, and battlefield tracking of assets/resources. Overall, the military, civilians, and the U.S. economy have all benefitted greatly resultant from the development of GPS.

The GPS system is considered a successful R&D program that transitioned to a production system with worldwide benefits through maturation and increased capability over time. This research needs to caveat the success of GPS with the frequent failure of other research initiatives. Most research endeavors don't experience the success and visibility of the GPS system. But there are two important principles that need to be understood regarding failure. One: failure should not be a deterrent from conducting the research. Failure is often used as a building block to success. Two: Lessons learned should always be extended to new initiatives. Any discoveries made during the research that did not necessarily lead to the desired conclusion/output can be leveraged to other efforts.

B. RELATION BACK TO THE THESIS STATEMENT

GPS is a fantastic example of why R&D needs to remain a priority for the U.S., and other private corporations and international governments should at a minimum acknowledge the potential large successes that could introduce paradigm shifts, providing an iteration of technological superiority over competitors or adversaries. Once acknowledged, the respective organizations can assess their competitive landscapes to determine the amount of resources that should be devoted to R&D. The development of GPS reinforces the notion that if think tanks are in existence, and are properly postured with personnel and resources to solve problems and/or produce good ideas, innovation will continue to occur. With innovation, our soldiers and civilians alike can reap the benefits of increased capability and gained efficiencies through technological progress and evolution. GPS illustrates why investments in R&D are worthwhile, and rationalizes why the U.S. should continue to invest in R&D. Today's instantiation of GPS has both tangible and intangible metrics associated with a massive Return On Investment (ROI). The intangible ROI partly consists of the discoveries and improvements in technology related to and compounded by its discovery. Many good ideas happen by accident. Many outputs and discoveries from R&D are side effects from the originally purposed R&D. GPS is precisely that.

C. RECOMMENDATION

Currently, and historically, DOD R&D receives budgetary increases in times of impending conflict engagement. A recommendation to ensure DOD R&D execution is properly timed and fed into the acquisition process is to place increased emphasis on R&D during peace time or toward the end of conflicts. Military intelligence serves as a feeder to relay battlefield operational needs, details of future adversaries, and environments of future conflict to the entities conducting R&D. This R&D directly supports the development of the weapons systems required to defeat enemies and engage adversaries in their respective environments. Procurement should be at its peak during wartime. If the U.S. is executing extensive R&D of required capabilities while actively engaged with an enemy, it is already behind and at significant risk for longer conflict, higher cost to defend the nation, and loss of life. R&D needs to be conducted early and continuously.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

1957, Soviet Union launches Sputnik. (n.d.). Retrieved from http://www.history.com/this-day-in-history/soviet-union-launches-sputnik-i

A guide to the Global Positioning System (GPS). (n.d.). Retrieved from http://support.radioshack.com/support_tutorials/gps/gps_tmline.htm

Allegany Ballistics Laboratory. (n.d.). In *Wikipedia*. Retrieved August 5, 2016, from https://en.wikipedia.org/wiki/Allegany_Ballistics_Laboratory

Alterman, E. (2012). Think Again: Is defense R&D spending effective? *Center for American Progress.* Retrieved from https://www.americanprogress.org/issues/general/news/2012/01/13/11001/think-again-is-defense-rd-spending-effective/

Amadeo, K. (2016a). U.S. GDP by year compared to recessions and major events. About.com. Retrieved from http://useconomy.about.com/od/GDP-by-Year/a/U.S.-GDP-History.htm

Amadeo, K. (2016b). Federal budget process. Retrieved from http://useconomy.about.com/od/fiscalpolicy/p/Who_budget.htm

Appelbaum, B. (2012). A shrinking military budget may take neighbors with it. *New York Times*. Retrieved from http://www.nytimes.com/2012/01/07/us/a-hidden-cost-of-military-cuts-could-be-invention-and-its-industries.html?_r=4

Christensen, M. D. (2012, July). The executive budget process: An overview. Congressional Research Service, Library of Congress. Retrieved from https://www.fas.org/sgp/crs/misc/R42633.pdf.

Congress, U.S. Office of Technology Assessment (1993). *Defense conversion: Redirecting R&D.* Washington: Government Printing Office.

Defense conversion: Redirecting research and development. (1993). DIANE Publishing Co. Retrieved from https://books.google.com/books?id=FOHYI3K75KQC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

Dissinger, K. (2008). GPS goes to war-The Global Positioning System in Operation Desert Storm. *Army Heritage Museum*.

Dziadczyk, E., Zabierowski, W., & Napieralski, A. (1957). Satellite navigation system GPS. In *CADSM'2007; 9th International Conference The Experience Of Designing And Application Of Cad Systems In Microelectronics*.

Ehrhard, T. (2008). Integrating disruptive technologies in DOD. Retrieved from www.dtic.mil/ndia/2008disruptive/Ehrhard.pdf

Encyclopedia of the New American Nation. (n.d.). Science and technology – World War II and the Early Cold War. Retrieved from http://www.americanforeignrelations.com/O-W/Science-and-Technology-World-war-ii-and-the-early-cold-war.html

Enge, P., & Misra, P. (1999). Scanning the issue/technology: special issue on global position system. *Proc. of the IEEE*, *87*(1). Retrieved from http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=736338

Etter, M. D. (2001). A Glimpse into the DOD S&T program. Retrieved from https://www.nae.edu/Publications/Bridge/ScienceTechnologyMilitaryExperimentation/AGlimpseintotheDODSTProgram.aspx

Finnamore, C. (2015). Top inventions and technical innovations of World War 2. Retrieved from http://www.expertreviews.co.uk/technology/7907/top-inventions-and-technical-innovations-of-world-war-2

Forman, P. (1987). Behind quantum electronics: National security as basis for physical research in the United States, 1940–1960. *Historical Studies in the Physical and Biological Sciences*, *18*(1), 149–229. Retrieved from https://www.researchgate.net/profile/Paul_Forman2/publication/245583374_Behind_quantum_electronics_National_security_as_basis_for_physical_research_in_the_United_States_1/links/0deec535b155d6496c000000.pdf

Garfield, E. (1987). The scientist: The military threat to R&D. Retrieved from http://www.the-scientist.com/?articles.view/articleNo/8748/title/The-Military-Threat-to-R-D/

Ghoshroy, S. (2011). Restructuring defense R&D. *Bulletin of the Atomic Scientists*, *20*. Retrieved from http://thebulletin.org/restructuring-defense-rd

GPS.gov. (2012). What is GPS? Retrieved April 26, 2016 from http://www.gps.gov/

Hagel, C. (2014). *Quadrennial defense review*. Washington, DC: Department of Defense, March, 4, 2014. Retrieved from http://archive.defense.gov/pubs/2014_Quadrennial_Defense_Review.pdf

Hallion, R. (1995). Precision guided munitions and the new era of warfare. Retrieved from http://fas.org/man/DOD-101/sys/smart/docs/paper53.htm

Harwit, M. (2013). In search of the true universe. Cambridge University Press. (Mansfield Amendment p. 145)

Hourihan, M., & Parkes, D. (2016). Federal R&D in the FY 2016 Budget: An Overview. Retrieved from http://www.aaas.org/fy16budget/federal-rd-fy-2016-budget-overview

Hruby, J. M., Manley, D. K., Stoltz, R. E., Webb, E. K., & Woodard, J. B. (2011). The Evolution of federally funded research & development centers. *Public Interest Report, Federation of American Scientists*.

Infoplease.com. Center for defense information, U.S. Military spending, 1946–2009. Retrieved from http://www.infoplease.com/ipa/A0904490.html

Jansky & Bailey. (1962). The Loran-C system of navigation. Retrieved from http://www.loran-history.info/Loran-C/Jansky%20_%20Bailey%201962.pdf

Johnson, C. W., & Yepez, A. A. (2010). Safety Cases for global navigation satellite systems safety of life (SoL) applications. *Proceedings of the International Association for the Advancement of Space Safety*. Huntsville Alabama, NASA/ ESA.

Johnson, S. (2010a) Where good ideas come from. Retrieved from http://www.derekchristensen.com/tracking-sputnick/

Johnson, S. (2010b) Where good ideas come from [Video]. Retrieved from https://www.ted.com/talks/steven_johnson_where_good_ideas_come_from/transcript?language=en

Kester, Kent COL. (n.d.). DOD factsheet. Retrieved from http://www.researchamerica.org/sites/default/files/uploads/DODFactsheet.pdf

Lee, J. (n.d). The Manhattan Project. U.S. history, 51f. The Manhattan Project. Retrieved from http://www.ushistory.org/us/51f.asp

Leitenberg, M. (2000). Studies of military R&D and weapons development; The role of scientific research in weapon development: What is Military R&D and how does it work? Retrieved from http://fas.org/man/eprint/leitenberg/tables.pdf

Leveson, I. (2015). The economic benefits of GPS. Retrieved from http://gpsworld.com/the-economic-benefits-of-gps/

Master government list of federally funded R&D centers (2016). Retrieved from http://www.nsf.gov/statistics/ffrdclist/#agency

National Science Board (U.S.). (2010). Globalization of Science and Engineering Research. National Science Board. Retrieved from http://wayback.archive-it.org/5902/20150818154444/http://www.nsf.gov/statistics/nsb1003/definitions.htm

National Science Foundation. (1994). Master Government List of *federally funded research and development Centers, Fiscal Year 1995*. Arlington, VA: National Science Foundation.

National Science Foundation, National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development, FYs 2010–12. Retrieved from http://www.nsf.gov/statistics/nsf13326/content.cfm?pub_id=4243&id=2

National Science Foundation, National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development, FYs 2014–16. Retrieved from http://www.nsf.gov/statistics/nsf13326/content.cfm?pub_id=4243&id=2

Nichols, R. H. (1974). *Geodetic SECOR satellite* (No. ETL-TR-74-6). Army Engineer Topographic Labs, Fort Belvoir, VA.

NSF.gov. (2014). Chapter 4: Research and Development: National Trends and International Comparisons. Retrieved from http://www.nsf.gov/statistics/seind14/index.cfm/chapter-4/c4s2.htm

Office of Technology Assessment. (1994). Assessing the potential for civil-military integration: Technologies, processes, and practices. (p. 145). Diane Publishing Co. Retrieved from http://www.dianepublishing.net/ProductDetails.asp?ProductCode=142892048X

Office of the Under Secretary of Defense for Acquisition Technology and Logistics. (2012). Report of the Defense Science Board Task Force on basic research. Washington, D.C., 20301 -3140. Retrieved from http://www.acq.osd.mil/dsb/reports/BasicResearch.pdf

Pace, S., Frost, G., Lachow, I., Frelinger, D., Fossum, D., Wassem, D. K. … Pinto, M. (1995). The Global Positioning System, chapter GPS history, chronology and budgets. RAND Corporation, 237–270.

Pellerin, C. (2014). Medical research institute contributes to vaccine development effort. Retrieved from http://www.defense.gov/News/Article/Article/603544

Poole, I. (n.d.). GPS history, dates & timeline. Radio-electronics.com. Retrieved from http://www.radio-electronics.com/info/satellite/gps/history-dates.php

Portree, D. S. (1998). *NASA's origins and the dawn of the space age*. NASA History Division, Office of Policy and Plans, NASA Headquarters.

Pullen, J. (2015). You asked: How do driverless cars work? Retrieved from http://time.com/3719270/you-asked-how-do-driverless-cars-work/

Raju, P. L. N. (n.d.). Fundamentals of GPS. Retrieved from http://www.wamis.org/agm/pubs/agm8/Paper-7.pdf

RAND Corporation. (1998). Government-wide and DOD definitions of R&D. *DOD financial management regulation* (Volume 2B, Chapter 5). Government-Wide. OMB Circular No. A-11 (1998). Retrieved from https://www.rand.org/content/dam/rand/pubs/monograph_reports/MR1194/MR1194.appb.pdf

Rao, J. (2008). Navigating by the stars. Retrieved from http://www.space.com/5849-navigating-stars.html

Ridenour, L. N. (1951). Science and the federal government. *Bulletin of the Atomic Scientists*, *7*(2), 35–37.

Ronald Reagan's military buildup. (n.d.). Retrieved from http://www.u-s-history.com/pages/h1957.html

Schwartz , M., Ginsberg, W., & Sargent, J. F. (2015). Defense acquisitions: How and where DOD Spends its contracting dollars. Retrieved from https://www.fas.org/sgp/crs/natsec/R44010.pdf

Smith, K. (2009). GPS technology in policing: Ride the wave to make better decisions. Retrieved from http://www.policechiefmagazine.org/magazine/index.cfm?fuseaction=display_arch&article_id=1778&issue_id=42009

Spiers, E. M. (2000). *Weapons of Mass Destruction*. UK: Palgrave Macmillan.

Steinbock, D. (2014). The challenges for America's defense innovation. *Information Technology and Innovation Foundation, Washington, DC*, 6.

Sullivan, M. (2012). A Brief history of GPS. Retrieved from http://www.pcworld.com/article/2000276/a-brief-history-of-gps.html

Satellites, rockets and more. (2010). *The JHU Gazette March.* Retrieved from http://archive.gazette.jhu.edu/2010/03/01/satellites-rockets-and-more/

Transit satellite. (n.d.). In *Wikipedia*. Retrieved Aug 27, 2016, from https://en.wikipedia.org/wiki/Transit_(satellite)

U.S. Congress, Office of Technology Assessment. (1995). *A history of the Department of Defense federally funded research and development centers* (OTA-BP-ISS-157; GPO stock #052-003-01420-3). Retrieved from https://www.princeton.edu/~ota/disk1/1995/9501/9501.PDF

U.S. Department of Defense**,** Office of the Secretary of Defense, Deputy Director of Defense Research and Engineering/Science and Technology, Department of Defense. (1992). *In-House RDT&E Activities: Management Analysis Report for Fiscal Year 1990.* Washington, DC: Author, pp. vi-xiv.

United States Congress, Office of Technology Assessment. (1992). *Building future security: Strategies for restructuring the defense technology and industrial base*. Washington, DC, Author.

United States General Accounting Office. (1995). *GAO/HR-95-4 Defense Weapons System Acquisition*. Retrieved from http://www.gao.gov/assets/230/220907.pdf

Wade, M. (1997). Transit. Retrieved from http://www.astronautix.com/t/transit.html

Weiss, R. & Vahey, M. (2014). The FY 2015 science and technology R&D budget. Retrieved from https://www.whitehouse.gov/sites/default/files/microsites/ostp/2015%20Budget%20Release.pdf

Wooley, L. (2006). Human events: Bill Clinton and the decline of the military. Retrieved from http://humanevents.com/2006/12/21/bill-clinton-and-the-decline-of-the-military/

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California